Using Graphical Representation of User Interfaces as Visual References

by

Tsung-Hsiang Chang

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Abstract

My thesis investigates using a graphical representation of user interfaces - screenshots - as a direct visual reference to support various kinds of applications. We have built several systems to demonstrate and validate this idea in domains like searching documentation, GUI automation and testing, and cross-device information migration. In particular, Sikuli Search enables users to search documentation using screenshots of GUI elements instead of keywords. Sikuli Script enables users to programmatically control GUIs without support from the underlying applications. Sikuli Test lets GUI developers and testers create test scripts without coding. Deep Shot introduces a framework and interaction techniques to migrate work states across heterogeneous devices in one action, taking a picture. We also discuss challenges inherent in screenshot-based interactions and propose potential solutions and directions of future research.

Thesis Supervisor: Rob Miller
Title: Associate Professor

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Chapter 1

Introduction

In human-to-human communication, people communicate with each other verbally and visually. However, sometimes it is difficult to verbally describe something. In that case, we use pictures as visual references. For example, to find a missing dog, we would not post flyers with only the dog's name. We would put the dog's picture on the flyer. For another example, we would say "I want a haircut like her" and show a hairstyle photo to the barber.

However, in human-to-computer communication, most interfaces do not interact with us visually and force us to rely on *non-visual alternatives*. An example is automation and testing for graphical user interfaces (GUIs). GUI automation and testing usually require writing scripts to send commands to particular GUI widgets in order to operate them and verify the correctness of their behavior. When one wants to write such scripts, one big challenge is: how to refer to a specific widget in a script?

Common solutions are using the pre-programed name of the widget, which may be unfamiliar or even unavailable to the users, or using screen location, such as (x, y), which is very brittle as the widget is not likely to stay at the same place. Both solutions are examples of non-visual alternatives, which forces the users to learn a new way to operate the system they are already familiar with, and therefore damages the usability of the automation system.

Another example is searching for help. With the explosion of information on the web, search engines are increasingly useful as a *first* resort for help with an application. Searching the web currently requires coming up with the right keywords to describe the GUI element, which can be very challenging if there is no title or textual label available around.

We observe that these non-visual alternatives present certain limitations to GUI users as they perform various kinds of tasks. Motivated by these problems, we wonder why we cannot just use the user interface *itself* (i.e. its screenshot) as a reference.

This thesis explores the possibilities of using screenshots as a visual reference in various domains. We propose a new interaction model, *Screenshot-Driven Interaction*, a set of interaction techniques triggered by *taking a screenshot* to find information or issue commands involving GUI elements. We also contribute a series of work that embodies this interaction model and the idea of using screenshots as visual references. Furthermore, while developing these systems, we see new challenges ans obstacles coming up along with this new notion. To address them, we contribute a set of design principles and discuss the trade-off in our solutions.

1.1 Thesis Statement

A graphical representation of user interfaces can be used as direct a visual reference to enable new kinds of screenshot-driven interactions in domains like searching, GUI automation and testing, and cross-device information migration.

1.2 Screenshots as Reference in User Interface Design

Screenshots are not common design elements in modern GUI systems compared to text or graphical icons. However, a great potential of using screenshots as visual references in user interface design has emerged recently. Compared to the non-visual alternatives, taking screenshots is an intuitive way to specify a variety of GUI elements, applications, or devices. Most importantly, screenshots are *universally accessible* for all applications on all GUI platforms, since it is always possible to take a screenshot of the interface the users see.

Sikuli Search [49] is the first attempt to explore mixing screenshots into an interaction process. Sikuli Search allows a user to search documentation by taking a screenshot of a GUI widget instead of using key words to look up the application built-in help. After this, a similar idea is applied to writing GUI automation scripts and created Sikuli Script and IDE [49].

Standing on the basis of the Sikuli project, I have applied this idea to more problems, such as GUI testing and task migration across devices. While exploring the solutions to these problems, the following systems have been developed.

- Sikuli Test [12], a system based on Sikuli Script [49] that enables GUI developers and Quality Assurance (QA) testers to create test scripts to verify GUI behavior without writing code and facilitates applying good testing practices on GUI development.

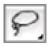
- Deep Shot [10], a framework for capturing the current work state of a task (e.g., the specific part of a document being viewed) and resuming it on a different device. Two new interaction techniques *deep shooting* and *deep posting* with Deep Shot, for pulling and pushing work states, respectively, using a mobile phone camera are introduced. For example, we can use a mobile phone camera to take a picture of a desktop monitor showing a map and continue to browse the same area of the map on the phone.

- PAX [11], a hybrid framework that associates the visual representation of user interfaces and their internal hierarchical metadata. This framework enhances the capability of existing pixel-based systems and allows them to reach not only the pixels of a user interface but also the internal structured data under the pixels.

In this section, I describe how screenshots can be used in various domains.

1.2.1 Searching Documents

Software becomes more and more complex as it evolves in a very fast pace. When a user has questions with using a particular feature in an application, searching on the web or looking up the application built-in help are the most common way to request help. In order to retrieve related documentation or web pages, these methods require the user to come up with right keywords, which can be very challenging. However, if there is a human expert around, the user may *directly point at* the user interface of the application and ask questions, such as "how do I use this tool?" or "why is this button grayed out?"

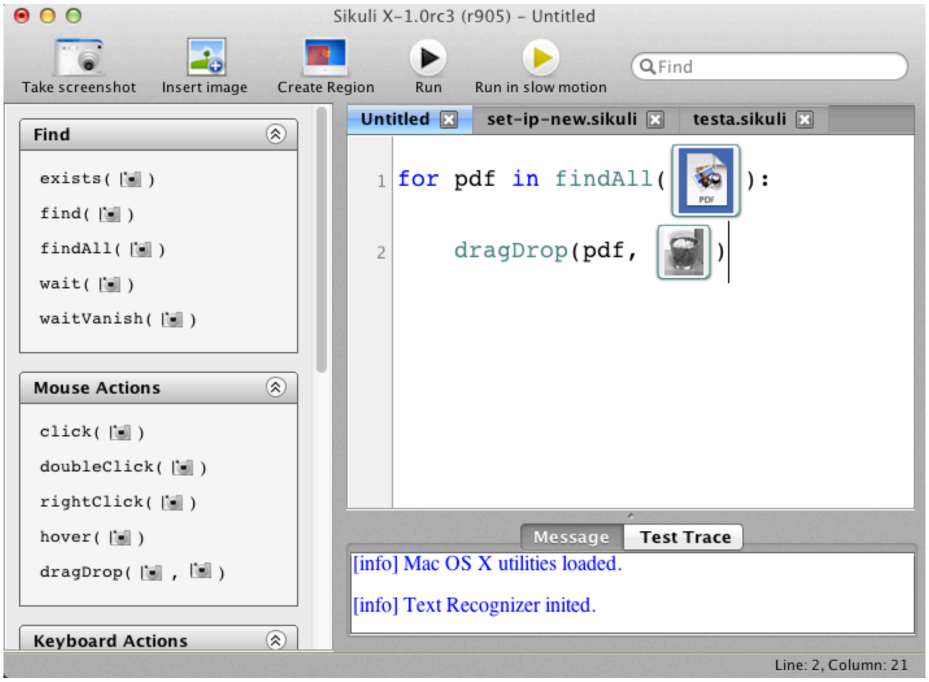
Yeh et al. [49] introduced Sikuli Search, which uses screenshots to search documentation about GUI elements. For example, a new user of Photoshop may search  in a collection of documents by taking a screenshot of it without knowing its name. In Sikuli Search, the interaction model consists of two steps: 1) the user takes a screenshot of a portion of the screen, which can be a GUI element, a paragraph of text, or a window; 2) the system retrieves documents related to the screenshot and present them to the user. According to the user study conducted in [49], the average time of a screenshot-based search is less than half time of a conventional keyword-based query, with no reduction in the quality of search results.

1.2.2 GUI Automation

GUI automation or scripting has been a challenging problem for a long time. The main difficulty is that there are no standard communication channels or protocols for GUI applications. Some well-engineered applications expose a set of API to other applications or properly follow a accessibility standard of the operating system, so there is a chance to communicate with them through these APIs. However, most applications do not have these kinds of designs, and therefore the only common element among all GUI applications is the *pixels* of the user interfaces.

In late 90's, Potter [34] was the first to explore the idea of analyzing the visual patterns on the screen and championed its potential for supporting application-independent end-user programming. About the same time, Zettlemoyer et al. [51] introduced VisMap and VisScript, which converts the GUI elements on the screen into structured objects and further allows a user to script the GUI with simple commands and those objects.

Recently, we introduced Sikuli Script [49], a scripting system that enables users to use screenshots of GUI widgets to control them programmatically. The system is based on Python, which gives its user the full power of a programming language to author an au-



```
for pdf in findAll( ):
    dragDrop(pdf, )
```

```
[info] Mac OS X utilities loaded.
[info] Text Recognizer inited.
```

Figure 1-1: Sikuli IDE is a script editor specifically designed for writing screenshot-based scripts.

tomation script. With Sikuli Script, we can ask the computer to “move all Word documents to the recycle bin” by using a command `dragDrop` and taking screenshots of a word document and a trash can respectively.

To facilitate writing automation scripts with screenshots, I developed Sikuli IDE, which is a development environment specifically designed for writing screenshot-based automation scripts (See Figure 1-1). In Sikuli IDE, screenshots are *first-class objects*, which can be assigned to variables, returned from a function, or passed as parameters. Every time a user needs to refer to a GUI element in a script, he/she can take a screenshot of the element by pressing the "Take screenshot" button on the toolbar or a hot key. The screenshot will be shown directly in the IDE and then can be used as a first-class object or be moved around in the script.

More details about Sikuli Script and IDE will be discussed in Chapter 3.

1.2.3 GUI Testing

Testing a GUI's visual behavior typically requires human testers to interact with the GUI and to observe whether the expected results of interaction are presented. This is a labor intensive task and has been a hard problem to automate because of the natural difficulty of GUI automation. However, since Sikuli Script has dealt with the problem of GUI automation with screenshots, it is natural to extend it beyond automation.

Based on Sikuli Script, I developed Sikuli Test, a system that allow GUI developers and QA testers to create test scripts to verify GUI behavior without writing code. Sikuli Test provides a new interaction model called *Test By Demonstration*, which generates Sikuli scripts along with the necessary screenshots by recording both the user's input and screen images.

Screenshots play the key role in Sikuli Test. In Sikuli Script, one only can write scripts and take screenshots manually. In contrast, in Sikuli Test, one can either use the old method or use the new recording mechanism, which continuously takes full screenshots and automatically crops the parts of target elements with computer vision algorithms.

In Chapter 4, I show screenshots can be effectively used to test a variety of GUI behavior and discuss how this approach can facilitate good testing practices, such as unit testing, regression testing, and test-driven development.

1.2.4 Task Migration Across Devices

A user task often spans multiple heterogeneous devices, e.g., working on a PC in the office and continuing the work on a laptop or a mobile phone while commuting on a shuttle. However, there is a lack of support for users to easily migrate their tasks across devices. To address this problem, I created Deep Shot, a framework for capturing the user's work state that is needed for a task (e.g., the specific part of a webpage being viewed) and resuming it on a different device.

Deep Shot provides two novel camera-based interaction techniques, *deep shooting* and *deep posting*. These two techniques allow seamless and intuitive migration of user tasks from one device to another by one uniform operation: taking pictures. Deep shooting

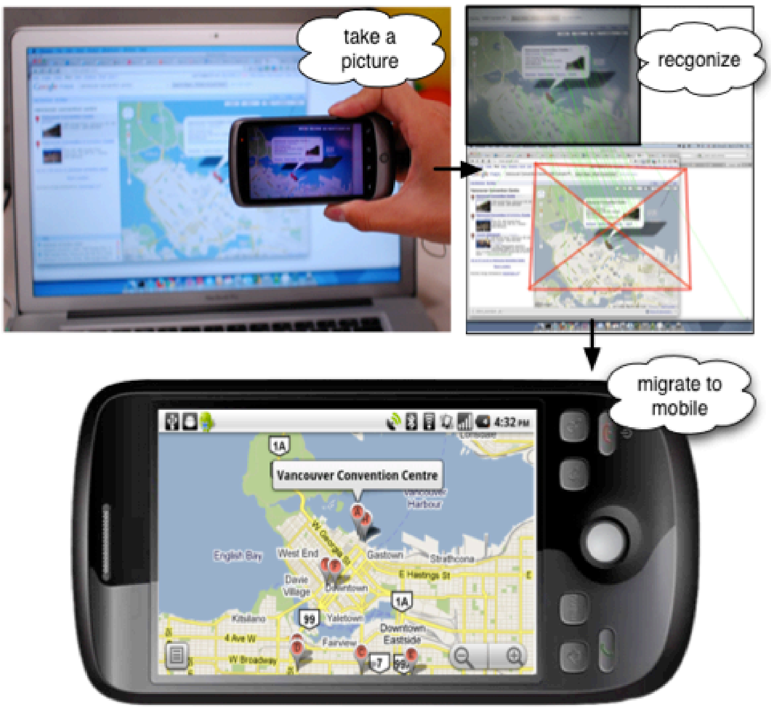


Figure 1-2: A user takes a picture of the screen of her computer and then sees the application with the current state on her phone. Our system recognizes the application that the user is looking through the camera, automatically migrates it onto the mobile phone, and recovers its state.

allows a user to capture and to persist the *deep information*, i.e., the information behind the raw pixels, such as application states, with a camera-like mobile phone application in a single click (see Figure 1-2). The work state captured with Deep Shooting can be resumed immediately on the mobile phone, opened later, or migrated to another device with deep posting. In contrast to with Deep Shooting, Deep posting uses a camera to *push* deep information (i.e. the work state) to another device and allows a user to resume the work on that device.

In Deep Shot, screenshots are used to identify the region of interest on a screen and also are the visual references to the target information. Unlike Sikuli Script and Test, the screenshot-driven interaction in Deep Shot is not triggered by taking a screenshot in a computer, but done by taking a photo of the screen using a different device.

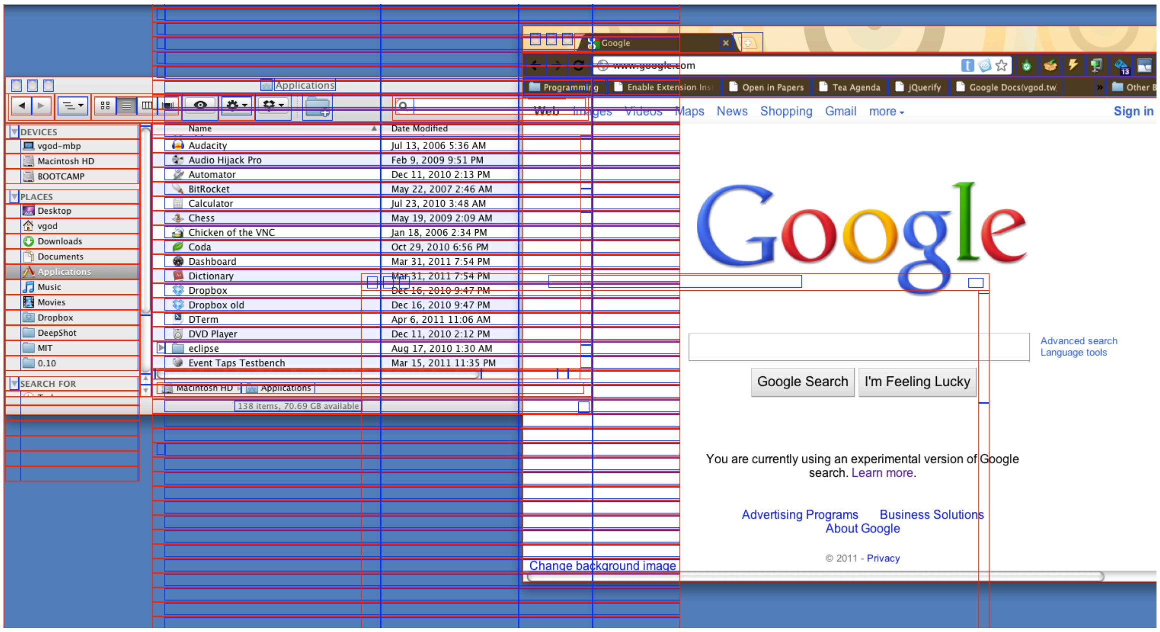
We demonstrate that Deep Shot can be used to support a range of everyday tasks migrating across devices. More details of Deep Shot are discussed in Chapter 5.

1.2.5 Combining Pixels and Accessibility Metadata

The screenshot-driven model is emerging as a new and promising way to develop new interaction techniques on top of existing user interfaces. However, in order to maintain platform independence, other available low-level information about GUI widgets, such as accessibility metadata, was neglected intentionally.

We observe that pixel representation of a user interface and its internal structures and metadata, such as accessibility information, *complement* each other. We present a hybrid framework, PAX, which combines *pixels and Accessibility APIs* to enhance the capabilities of current pixel-based systems and enables new interactive applications on top of existing interfaces.

PAX not only knows what is visible to the user on the screen but also understands the content and structures behind the pixels (Figure 1-3). We use accessibility metadata as a convenient and accurate source of widgets' information. If the accessibility metadata is not available, PAX automatically switches to pixel-level interpretation and still returns useful data. Furthermore, we use pixel-level methods to optimize the accessibility metadata. For



Name	Date Modified
Audacity	Jul 13, 2006 5:36 AM
Audio Hijack Pro	Feb 9, 2009 9:51 PM
Automator	Dec 11, 2010 2:13 PM
BitRocket	May 22, 2007 2:46 AM
Calculator	Jul 23, 2010 3:48 AM
Chess	May 19, 2009 2:09 AM
Chicken of the VNC	Jan 18, 2006 2:34 PM
Coda	Oct 29, 2010 6:56 PM
Dashboard	Mar 31, 2011 7:54 PM
Dictionary	Mar 31, 2011 7:54 PM
Dropbox	Dec 16, 2010 9:47 PM
Dropbox old	Dec 16, 2010 9:47 PM
DTerm	Apr 6, 2011 11:06 AM
DVD Player	Dec 11, 2010 2:12 PM
eclipse	Aug 17, 2010 1:30 AM
Event Taps Testbench	Mar 15, 2011 11:35 PM

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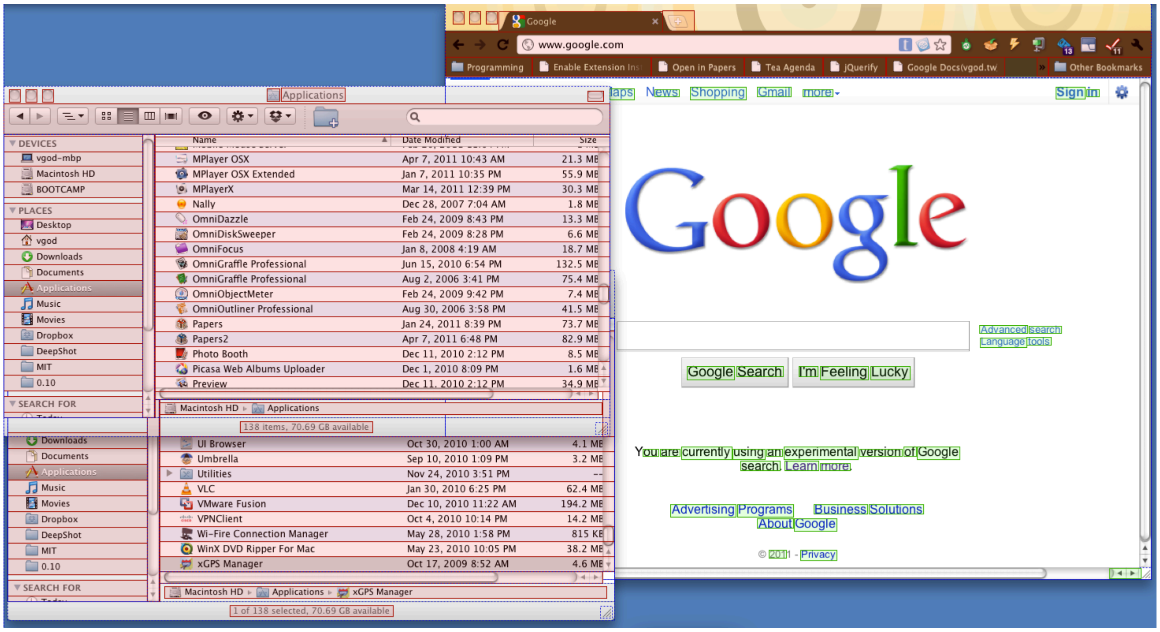
(a) The internal structure of a GUI given by Accessibility APIs (AX) may not necessarily correspond to the actual visual representation of the GUI. Boxes above indicate the windows and widgets returned by AX even though they are not visible to users.



Name	Date Modified	Size
MPlayer OSX	Apr 7, 2011 10:43 AM	21.3 MB
MPlayer OSX Extended	Jan 7, 2011 10:35 PM	55.9 MB
MPlayerX	Mar 14, 2011 12:39 PM	30.3 MB
Nally	Dec 28, 2007 7:04 AM	1.8 MB
OmniDazzle	Feb 24, 2009 8:43 PM	13.3 MB
OmniDiskSweeper	Feb 24, 2009 8:28 PM	6.6 MB
OmniFocus	Jan 8, 2008 4:19 AM	18.7 MB
OmniGraffle Professional	Jun 15, 2010 6:54 PM	132.5 MB
OmniGraffle Professional	Aug 2, 2006 3:41 PM	75.4 MB
OmniObjectMeter	Feb 24, 2009 9:42 PM	7.4 MB
OmniOutliner Professional	Aug 30, 2006 3:58 PM	41.5 MB
Papers	Jan 24, 2011 8:39 PM	73.7 MB
Papers2	Apr 7, 2011 6:48 PM	82.9 MB
Photo Booth	Dec 11, 2010 2:12 PM	8.5 MB
Picasa Web Albums Uploader	Dec 1, 2010 8:09 PM	1.6 MB
Preview	Dec 11, 2010 2:12 PM	34.9 MB

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138 items, 70.69 GB available

Name	Date Modified	Size
UI Browser	Oct 30, 2010 1:00 AM	4.1 MB
Umbrella	Sep 10, 2010 1:09 PM	3.2 MB
Utilities	Nov 24, 2010 3:51 PM	--
VLC	Jan 30, 2010 6:25 PM	62.4 MB
VMware Fusion	Dec 10, 2010 11:22 AM	194.2 MB
VPNClient	Oct 4, 2010 10:14 PM	14.2 MB
Wi-Fire Connection Manager	May 28, 2010 1:58 PM	815 KB
WinX DVD Ripper For Mac	May 23, 2010 10:05 PM	38.2 MB
xGPS Manager	Oct 17, 2009 8:52 AM	4.6 MB

Macintosh HD ▸ Applications ▸ xGPS Manager

1 of 138 selected, 70.69 GB available

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(b) PAX combines pixels and Accessibility APIs for more accurate association between the visual representation and internal structure of a GUI. It filters accessibility information for only visible objects (red boxes) and also provides role, content, location, and size of objects detected by pixel-based methods (green boxes).

Figure 1-3: Comparison between Accessibility metadata and PAX.

instance, when accessibility APIs are not fine-grained enough to return the position of each word in a paragraph of text, we use a pixel-based segmentation algorithm, along with the known text for the whole paragraph obtained from the accessibility API, to locate the words with high precision.

PAX can be used to enhance existing pixel-based systems. For example, we enhance Sikuli Script so that it can read the value of a slider on a GUI, which is not shown on the screen at all, and preserve the readability of its script code at the same time. We also create two novel applications, Screen Search and Screen Copy, to demonstrate how PAX can be applied to development of desktop-level interactive systems. The details of PAX are discussed in Chapter 6.

1.3 Common Pitfalls and Remedies

As we develop new systems with the screenshot-driven model, we see new interesting and promising applications as well as pitfalls due to the nature of pixel matching. We categorize these pitfalls into four common problems as follows, where the target is defined as the screenshot taken by the user.

- The target is not visible.
- The target changes its look over time.
- The target can not be uniquely identified.
- The target is indistinguishable in different states.

These problems can be caused by various reasons. For example, the invisibility problem could be caused by occlusion or scrolling out of view. For each problem, we suggest some design principles to overcome it from the perspective of the system designers as well as the users. Each of these design principles are discussed in Chapter 7.

1.4 Contribution

In this thesis, I contribute the following ideas, designs, and systems.

- The idea of using screenshots as visual references in user interface design.
- A new interaction model, Screenshot-driven Interaction.
- The design and implementation of Sikuli Script's API and Sikuli IDE.
- Sikuli Test: using screenshots to support GUI testing.
- Deep Shot: using screenshots to support task migration across devices.
- PAX: associating screenshots and their internal metadata to enhance pixel-based systems.
- A list of common pitfalls in pixel-based systems and their remedies.

Chapter 2

Related Work

2.1 Screenshot-Driven Interaction

The idea of supporting interactions by analyzing the visual patterns rendered on the screen was examined in the late 90's. Potter [34] was the first to explore this idea and referred to it as direct pixel access. He also championed its potential for supporting application-independent end-user programming. His Triggers system supported novel visual tasks such as graphical search-and-replace and simulated floating menus. While Triggers can be configured through an interactive dialog to perform some basic tasks similar to the Sikuli Script examples presented earlier, it is not a full scripting language and does not support fuzzy matching.

Zettlemoyer & St. Amant [51] described VisMap and VisScript. VisMap inferred high-level, structured representations of interface objects from their appearances using a rule-based system and generated mouse and keyboard gestures to manipulate these objects. However, VisMap is not independent of platforms and requires lots of rules to define each individual GUI widget. VisScript provided a basic set of scripting commands (mouse-move, single-click, double-click and move-mouse-to-text) based on the output of VisMap, but was not integrated with a full-feature scripting language. WinCuts allowed users to cut a sub-region of an existing window and create an independent live view of the source, but did not interpret its content [42].

While these early pioneering works shed light on the potential of image-based interaction, they led to almost no follow-up work, mostly because the practicality was limited by the hardware and computer vision algorithms of the time. However, faster hardware and recent advances in vision algorithms particularly those based on invariant local features have now presented us with an opportunity to reexamine this idea and develop practical image-based interactive applications.

2.2 Visual References in Programming and GUI Testing

Conventional programming languages are difficult to learn and use, and may require months to years of training. Visual Programming systems have been attempting to simplify programming using images and graphics since 1980s [18, 31]. These systems allow users to create a program in a two-dimensional canvas, which makes programming easier but also difficult to scale. Simonyi introduced a notion called Intentional Programming [38], which separates source code storage and presentation so a piece of code can have different views depending on its scenario. For example, a function can be viewed as a mathematical formula or a circuit diagram depending on which kind of code it is. Barista [22] provides a highly visual and interactive code editor that shows images, mathematical formulas, or a "match form" view of a logical expression to improve people's comprehension over their textual versions.

Inspired by these prior works, Sikuli IDE shows screenshots as visual references in its code editor for better readability of scripts. Although a user still needs to type commands and take a screenshot of the targets, there is no need to be familiar with additional application interfaces for merely automation.

The barrier to learn programming could be overcome by creating a Programming By Demonstration (PBD) system based on screenshots. As early as early 90's, Singh et al. [39] proposed the Sage system that can capture and store GUI interactions demonstrated by users as reusable templates. Wilcox et al. [47] illustrated the value of visual feedback in programming by demonstration tools especially during the testing process, a finding validates the design decision of Sikuli Test to embed visual feedback directly in test scripts. Given the popularity of Web-based applications, the Koala system by Little et al. [26] and the CoScripter system by Leshed et al. [23] both aim to enable Web users to capture,share, automate, and personalize business processes. Based on VisMap, St. Amant et al. [40] then described several techniques of visual generalization for PBD by observing user behavior and inferring general patterns based on the visual properties and relationships of user interface objects. Their work then enlightened the possibility of real-time screen analysis of screen images by PBD systems.

In relation to these works, Sikuli Test extends PBD to serve a new purpose — GUI testing, and is also applicable to any Web-based GUI as long as its visual feedback is observable.

2.3 Screenshot-Driven Information Migration

Several research projects have addressed the issues of migrating information across devices. Pick-and-drop [35] is a direct-manipulation technique to pick up an object on a computer and drop it on another using a pen. Hyperdragging [36] is a technique like drag-and-drop that transfers information across devices. However, these two techniques require special, uncommon devices (pen devices and augmented tabletops) so they cannot be easily deployed to the real world.

Remote Clip [30] is a simple way to share information via a synchronized clipboard across multiple personal computers. Unlike Pick-and-drop and Hyperdragging, there are no special hardware requirements for Remote Clip. However, this technique is only feasible for copying textual or selectable objects.

Some tools [9, 42] allow users to control applications remotely. In contrast, we propose Deep Shot in this thesis to allow users to interact with the same content via native applications running on a local device, which eliminates the need to have a constant network connection.

Associating physical tags or bar codes to digital files is also a way to migrate information. Want et al. [46] describes using RFID tags to link physical objects to network services. Android and iPhone users can install an application by scanning a QR code. The downside of these techniques is that they require special tags or codes that can only be read by machines. In contrast, graphical user interfaces are already there on the screen for being used by humans. The screenshots of the GUI can also be recognized by machines and do not occupy additional spaces on the screen.

On the other hand, some techniques based on only visual features have been proposed. PACER [25] allows a user to interact with a paper's digital version based on its visual features on a mobile phone. Shoot & Copy [8] allows a user to take a picture of file icons on a large display with a mobile phone, and the list of files will be stored in the phone. The list of files can then be transfered to another computer using Bluetooth. Shoot & Copy uses ad-hoc image processing algorithms specifically designed for file icons on a solid-color desktop. Therefore, it can not be extended to migrate general information or even application states across devices.

Liu et al. described a system to drag and drop documents with a mobile camera [27]. This system requires the user to take one picture of the source document and another of the destination computer. Once the source and the destination are identified, the document is transfered across these two devices through WiFi.

Compared to these systems, we used similar feature matching algorithms in Deep Shot. However, these techniques only focused on file transfer or document manipulation for certain applications. In contrast, Deep Shot provides an extensible framework that enables an arbitrary application to migrate not only its content but also its runtime states across devices using a mobile phone camera.

2.4 Connecting Screenshots and the Metadata of a UI

Recently, more pixel- or screenshot-based work has emerged. Screen-Crayons allows a user to create annotation or highlight on any type of document with pixel-based techniques [32]. Mnemonic Rendering determines the visibility of applications and shows motion trails of the changes when the hidden parts of windows are being revealed [6]. Prefab interprets the pixels of a GUI and generates a high-level model of the widgets and their hierarchy [14, 15]. The characteristic common to all this prior work is that it is completely focused on the pixel level. Instead of pure pixel methods, we propose a hybrid approach in this thesis that leverages pixels and other structured information (e.g. accessibility metadata) from the operating system to boost the robustness and performance of existing work and to enable new applications.

Most modern operating systems and GUI toolkits support Accessibility APIs, which were originally designed to be a standard hook for assistive technology applications, such as screen readers, or for GUI automation tools to communicate with a user interface programmatically. In addition to the assistive use of accessibility information, Stuerzlinger et al.'s User Interface Facades uses such information to allow users to customize an interface with copy-and-paste [41].

However, accessibility APIs are not widely available in every application and GUI widget. Hurst et al. reported that the Microsoft accessibility API can only correctly identify 74% of targets in eight popular applications on Windows [21]. Thus, instead of using only accessibility API, they developed a hybrid approach that feeds the visual representation (i.e. the pixels) of a user interface as well as accessibility metadata into machine learning algorithms to identify GUI targets with higher accuracy. However, their approach does not deal with content; it is mainly for post-analysis of interaction logs to identify what targets the users might have clicked. In contrast, the approach in this thesis is designed for real-time use to associate GUI widgets' internal metadata and their pixel representation.

Chapter 3

Sikuli

Sikuli [1] is our first attempt to apply screenshot-driven interaction to search documentation and GUI automation. [2] Sikuli allows users or programmers to make direct visual reference to GUI elements. To search a documentation database about a GUI element, a user can draw a rectangle around it and then Sikuli takes a screenshot as a query. Similarly, to automate interactions with a GUI element, a user can take a screenshot of the element and specify what keyboard or mouse actions to invoke when this element is seen on the screen. Compared to the non-visual alternatives, taking screenshots is an intuitive way to specify a variety of GUI elements. Also, screenshots are universally accessible for all applications on all GUI platforms, since it is always possible to take a screenshot of a GUI element.

In this chapter, two systems derived from the idea of Sikuli will be described.

The first system is Sikuli Search, which enables users to search a large collection of online documentation about GUI elements using screenshots. In this thesis, I will only discuss the screenshot-driven interaction used in Sikuli Search but not the algorithm design and implementation of the whole system, as those details are already covered in Yeh's doctoral dissertation [48].

The second system is Sikuli Script and IDE, a scripting system that enables program-

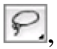
[1] In Huichol Indian language, Sikuli means "God's Eye", symbolic of the power of seeing and understanding things unknown.

[2] The work described in this chapter are collaborated with Tom Yeh, who designed and implemented the back-end computer vision algorithms of Sikuli Search and Sikuli Script. I designed and implemented the front-end of the systems, which includes their user interfaces and the API of Sikuli Script.

mers to use screenshots of GUI elements to control them programmatically. The system incorporates a full-featured scripting language (Python) and an editor interface specifically designed for writing screenshot-based automation scripts. Likewise, in this thesis, I will only focus on the user interfaces and the screenshot-driven interaction techniques in Sikuli Script and IDE. The details of computer vision algorithms used in this system are covered in [48].

3.1 Sikuli Search

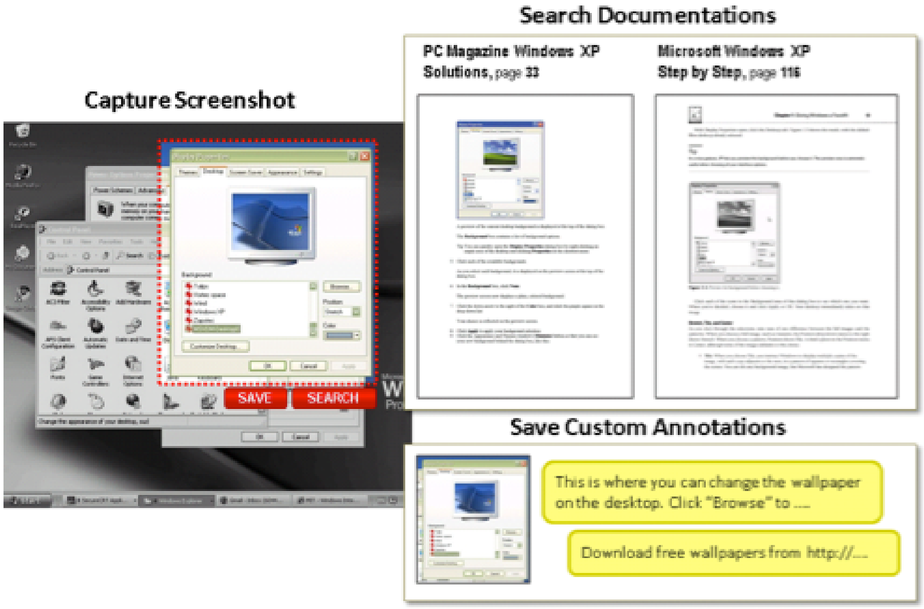
The development of Sikuli Search is motivated by the lack of an efficient and intuitive mechanism to search for documentation about a GUI element, such as a toolbar button, icon, dialog box, or error message. The ability to search for documentation about an arbitrary GUI element is crucial when users have trouble interacting with the element and the application's built-in help features are inadequate. Users may want to search not only the official documentation, but also computer books, blogs, forums, or online tutorials to find more help about the element.

Current approaches require users to enter keywords for the GUI elements in order to find information about them, but suitable keywords may not be immediately obvious. For example, for the users who are not familiar with Photoshop, it is unlikely they know how to use this tool , nor how to find information about it using keywords.

Instead of querying with keywords, we use a screenshot of the element as a query. Given their graphical nature, GUI elements can be most directly represented by screenshots. In addition, screenshots are accessible across all applications and platforms by all users, in contrast to other mechanisms, such as tooltips and help hotkeys (F1), which may or may not be implemented by the application.

3.1.1 Screenshot-Driven Search

Sikuli Search allows a user to select a region of interest on the screen, submit the image in the region as a query to the search engine, and browse the search results. To specify the region of interest, a user presses a hot-key to switch to Sikuli Search mode and begins


Search Documentations
PC Magazine Windows XP Solutions, page 33
Microsoft Windows XP Step by Step, page 116
Capture Screenshot
SAVE
SEARCH
Save Custom Annotations

This is where you can change the wallpaper on the desktop. Click "Browse" to ....

Download free wallpapers from http://....

Figure 3-1: Sikuli Search allows users to search documentation and save custom annotations for a GUI element using its screenshot (i.e., red rectangle).

to drag out a rubber-band rectangle around it (Figure 3-1). After the rectangle is drawn, a search button appears next to it, which submits the image in the rectangle as a query to the search engine and opens a web browser to display the results.

The backend database in Sikuli Search indexes screenshots extracted from a wide variety of resources using three kinds of features described as follows.

1. The text surrounding the screenshots in the source document, which is a typical approach taken by current keyword-based image search engines.

2. The SIFT feature descriptor [28] extracted from salient image locations of the screenshots, which is robust against variations in scale, translation, brightness, and rotation.

3. The embedded text in the screenshots extracted by optical character recognition (OCR) engines.

With these features of screenshots, users do not need to fit the rectangle perfectly around a GUI element while taking the screenshot. As a result, the whole interaction of searching with screenshots can be much faster than traditional keyword queries. According to the user study reported in [49], the average time of a screenshot-based search costs less than half time of a keyword-based query, whereas the quality of their search results have no significant differences.

3.2 Sikuli Script and IDE

The development of our visual scripting API for GUI automation is motivated by the desire to address the limitations of current automation approaches. Current approaches tend to require support from application developers. For example, AppleScript, Apple Automator, and Windows Scripting all require applications to provide APIs. Some systems (e.g. DocWizards [5], Chickenfoot [7], and CoScripter [23]) require accessible text labels for GUI elements. Some macro recorders (e.g. Jitbit [3] and QuicKeys [4]) achieve cross-application and cross-platform operability by capturing and replaying low-level mouse and keyboard events on a GUI element based on its absolute position on the desktop or relative position to the corner of its containing window. However, these positions may become invalid if the window is moved or if the elements in the window are rearranged due to resizing.

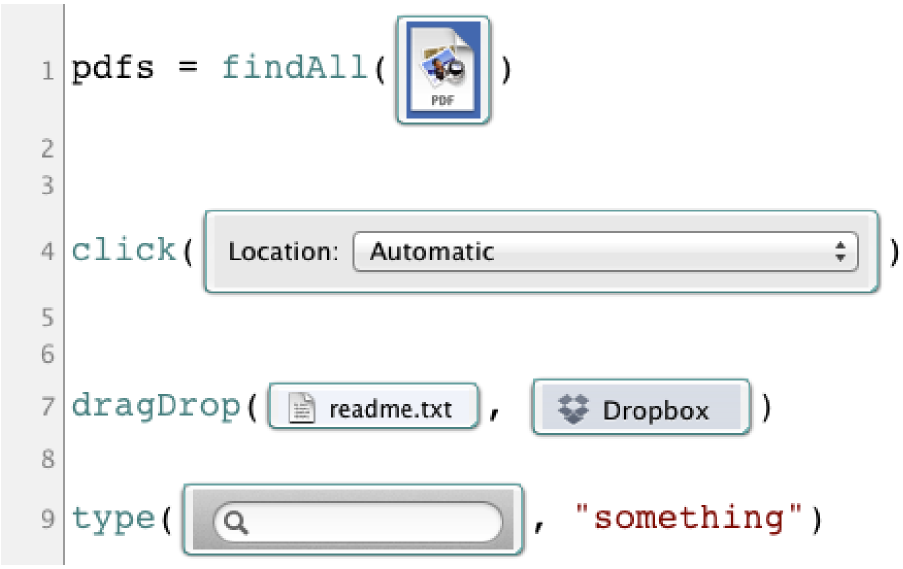
Therefore, we use screenshots of GUI elements directly in an automation script to programmatically control the elements with low-level keyboard and mouse input. (See Figure 3-2 for examples) Since screenshots are universally accessible across different applications and platforms, this approach is not limited to a specific application. Furthermore, the GUI element a programmer wishes to control can be dynamically located on the screen by its visual appearance, which eliminates the movement problem suffered by existing approaches.

3.2.1 Visual Scripting API

Sikuli Script provides a set of visual scripting API for GUI automation. The goal of this API is to give an existing full-featured programming language a set of image-based interactive

[3] http://www.jitbit.com/macrorecorder.aspx

[4] http://www.startly.com/products/qkx.html



```
1 pdfs = findAll(  )
2
3
4 click(  )
5
6
7 dragDrop(  ,  )
8
9 type(  , "something")
```

Figure 3-2: Examples of Sikuli commands. The first line finds all PDF icons on the screen and save them into a variable `pdfs`. Line 4 clicks on a drop-down box named Location and open it up. Line 7 drags a file “readme.txt” to a Dropbox folder. Line 9 types “something” into a search box.

capabilities. Although our API is currently optimized for Jython (the Python implementation on Java Virtual Machines), it should be straightforward to adapt it to other languages running on a JVM since it is built in Java.

The Sikuli Script API has several key components. The `find()` function takes a target pattern and returns screen a region matching the pattern. The `Pattern` and `Match` classes represent the target pattern and matching screen regions, respectively. A set of action commands invoke mouse and keyboard actions on screen regions. Finally, a visual hash table stores key-value pairs using images as keys. We describe these components in more detail below.

Find

The **find** function locates a particular GUI element to interact with. It takes a visual pattern that specifies the element’s appearance, searches the whole screen or part of the screen, and returns regions matching this pattern or null if no such region can be found. For example, `find( )` finds regions containing a Word document icon on the whole screen. In addition to `find`, another function `findAll` returns a list of all matching regions instead of the best one.

Pattern

The *Pattern* class is an abstraction for visual patterns. A pattern object can be created in three ways: taking a screenshot, from an image file, or from a string of text. When creating from an image, we use a computer vision algorithm *template matching* to find matching screen regions. When created from a string, OCR is used to find screen regions matching the text of the string. A pattern object has methods for tuning how general or specific matches must be. They are listed as follows.

- exact(), which indicates the pattern must be exactly matched;
- similar(*similarity*), which specifies how general (from 0.0 to 1.0) the matches can be;
- anyColor(), which indicates the pattern can match the same shape in any colors;
- anySize(), which indicates the pattern can match the same shape in any sizes;
- targetOffset(x, y), which specifies the click offset to the target (instead of the center by default).

Each method produces a new pattern, so they can be chained together. For example, `Pattern(🗎).similar(0.8).anyColor()` matches screen regions that are 80% of pixels similar to 🗎 of any color composition.

Region and Match

The *Region* class defines a rectangular region on a screen. Its attributes are x and y coordinates, height, width. The *Match* class extends the Region class and provides an abstraction for the screen region(s) returned by the `find()` function matching a given visual pattern. It has an additional attribute: similarity score. Typically, a `Match` object represents the best match, for example, `m = find(🗎)` stores the region found to look most like the icon in the variable m.

Another use of a Region object is to constrain the search to a particular region instead of the entire screen. For example, `find(`

`).find(`

`)` constrains the search space of the second find for the ok button to only the region occupied by the dialog box returned by the first `find()`.

To support other types of constrained search, our visual scripting API provides a versatile set of constraint operators: *left*, *right*, *above*, *below*, *nearby*, *inside*, *outside* in 2D screen space. (See Figure 3-3.)

These operators can be used in combination to express a rich set of search semantics For example,
`find(`

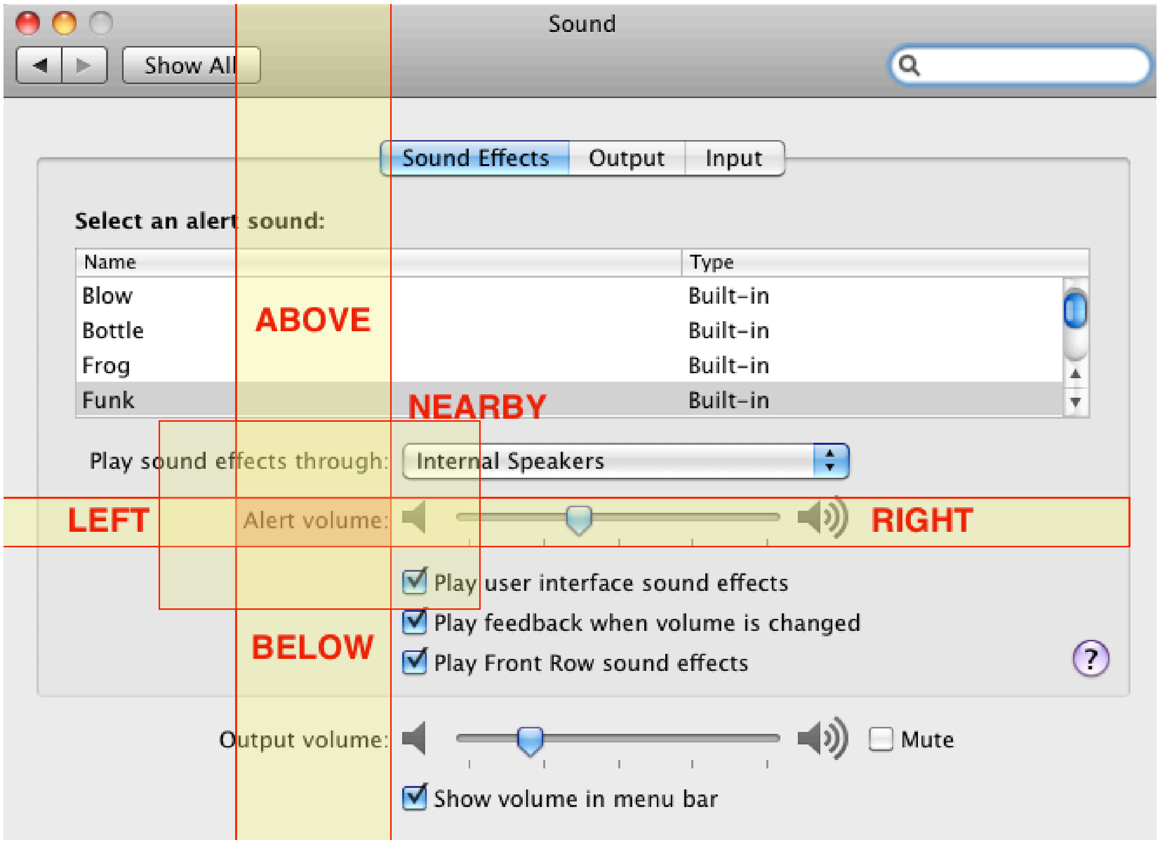
`).inside().find(` `).right().find(` `)` finds for the office toolbar first and then constrains the following searches within this matched area. The second `find()` searches for the office home button, and finally searches the disk icon within the region on the home button's right.

Action

The action commands specify what keyboard and/or mouse events to be issued to the center of a region found by find(). The core set of commands in our API are:

- **click**(*Pattern|Region*, [Modifiers]), **doubleClick**(*Region*, [Modifiers]): These two commands issue mouse-click events to the center of a target region. For example, `click(`) performs a single click on the best-matched close button found on the screen. If there are multiple matches with the same similarity score, the command clicks on any one of them randomly. Modifier keys such as Ctrl and Command can be passed as a second optional argument.

- **dragDrop**(*Pattern|Region* target, *Pattern|Region* destination): This command drags the element in the center of a target region and drops it in the center of a destination region. For example, `dragDrop(` ,) drags a word icon and drops it in the recycle bin.



Select an alert sound:

Name	Type
Blow	Built-in
Bottle	Built-in
Frog	Built-in
Funk	Built-in

Play sound effects through: Internal Speakers

Alert volume:

☑ Play user interface sound effects

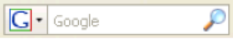
☑ Play feedback when volume is changed

☑ Play Front Row sound effects

Output volume: □ Mute

☑ Show volume in menu bar

Figure 3-3: Spatial operators are used to constrain matching regions. This figure lists the corresponding regions created with applying each spatial operator on the region "Alter volume".

- **type**(*Pattern|Region* target, String text): This command enters a given text in a target region by sending keystrokes to its center. For example, `type(`,"Sikuli") types the “Sikuli” in the Google search box.

Visual Hash Table

A visual hash table can be used to store key-value pairs using images as keys. It uses the same syntax as a typical Hash table in Python to create tables and to store values that need to be quickly retrieved (i.e., sub-linear time) by images. For example, `h = {` : "word", : "powerpoint"} creates a visual hash table associating two application names with their icon images. Then, `h[` `]` retrieves the string word, `h[` `]` = "excel" adds the string "excel" under its icon image, and `h[` `]` returns a null object.

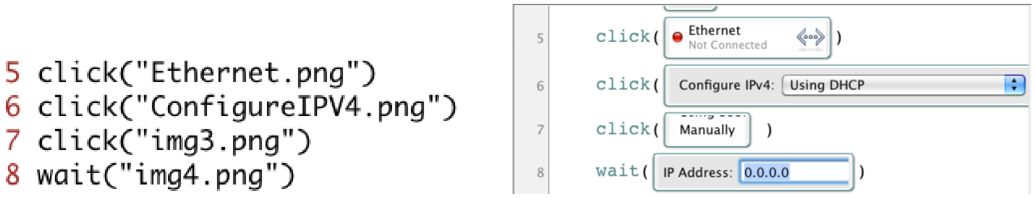
The visual hash table is useful for mapping a screenshot to an object. For example, when a user wants to write a poker robot script, a card on the screen needs to be interpreted as a suit and a number. This can be done with a visual hash table stored with 52 pairs of card images and their corresponding suits and numbers.

3.2.2 New API

Since we released Sikuli Script in 2009, its API has grown and becomes much more complete to be applied in many different scenarios and environments. The new set of API added since then are as follows.

- App class, which will be described in Chapter 6;
- global hotkeys, which allows a user to register a Sikuli function on a particular hotkey dynamically in a script;
- visual assertions, which will be described in Chapter 4;
- creating annotations and contextual help, which is described in a conference paper [50].

The comprehensive and up-to-date documentation of Sikuli Script can be found at http://sikuli.org/docx/.



```
5 click("Ethernet.png")
6 click("ConfigureIPV4.png")
7 click("img3.png")
8 wait("img4.png")
```

5 click(Ethernet Not Connected)
6 click(Configure IPv4: Using DHCP
7 click(Manually)
8 wait(IP Address: 0.0.0.0)

(a) A Sikuli script being viewed in a text editor.

(b) The same Sikuli script being viewed in Sikuli IDE.

Figure 3-4: Comparison between textual view and visual view of a Sikuli script.

3.2.3 Sikuli IDE

To facilitate writing screenshot-based scripts, we have developed Sikuli IDE. (Figure 1-1). Even without Sikuli IDE, a user still can write a Sikuli script with any text editor, as it is just a Jython script. However, Sikuli IDE provides two key functions that greatly lower the barrier to *read* and *write* such scripts.

Reading Screenshot-based Scripts

Screenshots are the key components in Sikuli scripts. Internally, a screenshot is simply represented as a string literal, which stores the path to the image file of the screenshot. In plain text or code editors, a script is shown as lines of textual strings. When users refer to a screenshot in such environments, they are actually using the string as *an indirect reference* to the image.

For example, in Figure 3-4(a), each line of code contains a string literal, which refers to an image file. If the images are well named, the user may be able to guess which GUI component on the screen the image refers to. However, a good naming mechanism needs some effort from script authors and can not be guaranteed. In the cases as the line 7 and 8 in Figure 3-4(a), there is no way to tell what the images are actually referring to.

To overcome this problem, I developed Sikuli IDE specifically for viewing and editing Sikuli scripts. In Sikuli IDE, screenshots are embedded in code as *direct visual references* (Figure 3-4(b)). This eliminates the problem that the user needs to guess which GUI element an image file actually refers to from its file name. The user can know exactly how the image files looks like directly in the editor.

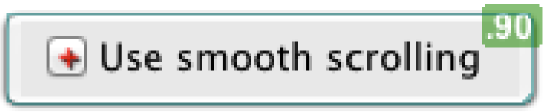


Figure 3-5: The similarity threshold for matching (.90 in this example) and the point of click (the red cross) can also be shown with screenshots.

Screenshots are used as visual patterns in Sikuli. Besides screenshots themselves, the similarity threshold for matching can also be shown with the images in the editor as in Figure 3-5.

3.2.4 Writing Screenshot-based Scripts

Embedding screenshots directly in Sikuli IDE enhances the readability of Sikuli scripts, but, how about writing such scripts?

As we mentioned earlier, the file name to a screenshot file is an indirect reference. Therefore, to fully employ the idea of using screenshots as visual references, it is necessary to avoid using file names in the interaction process. As a result, the process of taking screenshots in Sikuli IDE has been simplified into only two steps: 1) enter the screen capture mode by pressing either a hotkey or the button on the toolbar; and 2) drag a rectangular area around the target.

Once a user has taken a screenshot using Sikuli IDE, the screenshot is saved as an image file in the PNG format within the same folder of the script. The file name of the image file is determined automatically with a timestamp by default. In this way, the user does not need to come up with a name for the screenshot as well as where to save the file. The user only needs to care if the image shown in the editor can well represent the target on the screen.

In the capture mode of Sikuli IDE, the user only has one shot to stretch a rectangle around the target. In other words, once the mouse button is released, the rectangular area selected by the user is automatically captured. This design not only simplifies the capture process, but also forces the user not to carefully adjust the boundaries as Sikuli's fuzzy matching algorithm does not require strict boundaries.

3.2.5 Running and Debugging Scripts

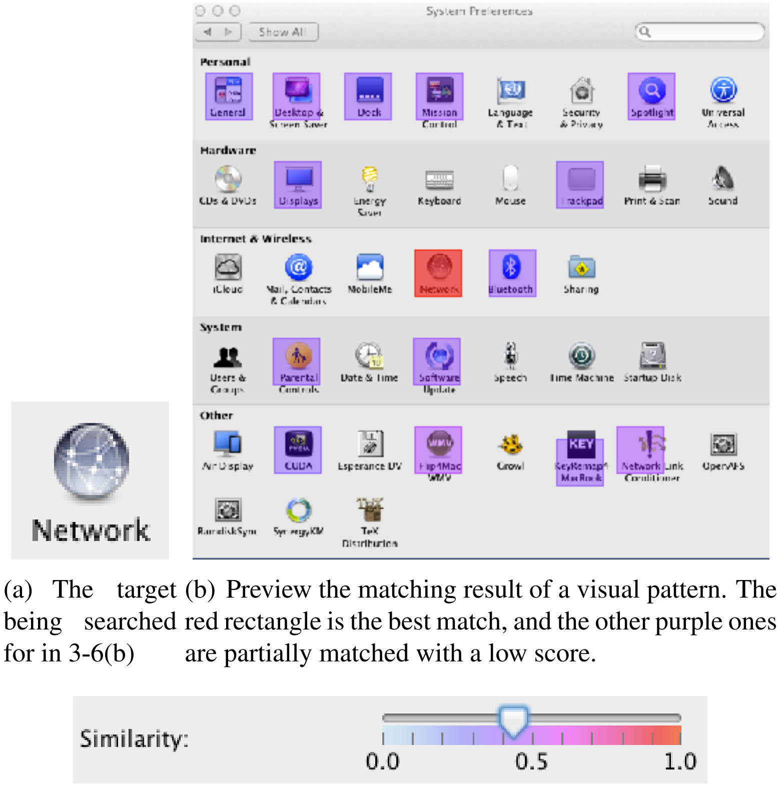
A script can be run in two different modes in Sikuli IDE. One is normal mode, which runs the script in full speed as a usual Jython script.

While running a script, Sikuli's automation engine visually identifies the target GUI component's current location (x', y') by searching the current screen for an image region matching the target image I. To find a given pattern, we apply the template matching technique with the *normalized correlation coefficient* implemented in OpenCV in our current system [49]. This technique treats the pattern as a template and compares the template to each region with the same size in an input image to find the region most similar to the template. Then, the click event is delivered to the center of the best matched region to simulate the desired user interaction.

The other one is "slow motion" (or debug) mode, which slows down the automation and highlights the best match of each target found on the screen. This mode effectively helps the user to debug the script and figure out if the visual patterns really match the expected target on the screen.

As for debugging, it is essential to know a visual pattern matches which portions of the screen and adjust the similarity threshold as needed. Sikuli IDE can preview how a pattern matches the current desktop (see Figure 3-6) under different similarity thresholds, so that these can be tuned to include only the desired regions. The editor also allows users to specify an arbitrary region of screen to confine the search to that region.

The editor also helps adjusting the click offset to the target. This is particularly useful when one wants to change the click position to somewhere else instead of the center of the target (Figure 3-7).

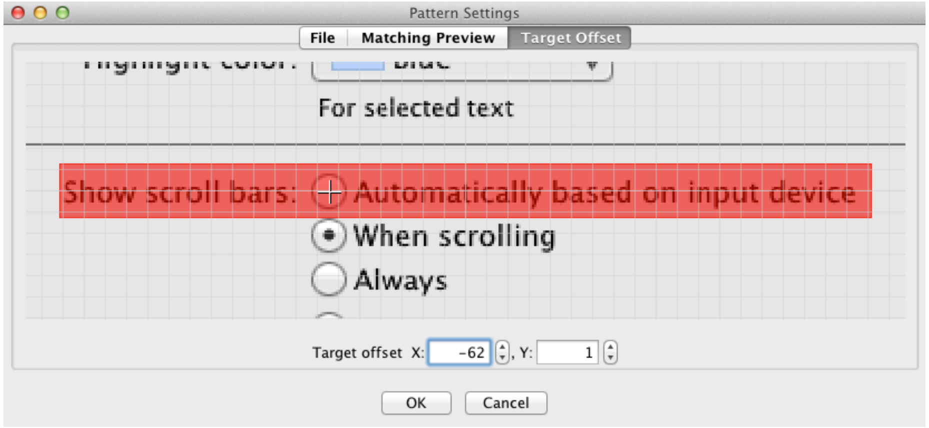


(a) The target being searched for in 3-6(b)

(b) Preview the matching result of a visual pattern. The red rectangle is the best match, and the other purple ones are partially matched with a low score.

(c) The slider for adjusting the similarity threshold.

Figure 3-6: The user can adjust the similarity threshold and preview the results under different settings. Here, the threshold is too low so there are many false positives (the purple areas).



Highlight color: Blue

For selected text

Show scroll bars: ○ Automatically based on input device
● When scrolling
○ Always

Target offset X: -62, Y: 1

Figure 3-7: The user can adjust the click offset to the target in the Sikuli IDE.

Chapter 4

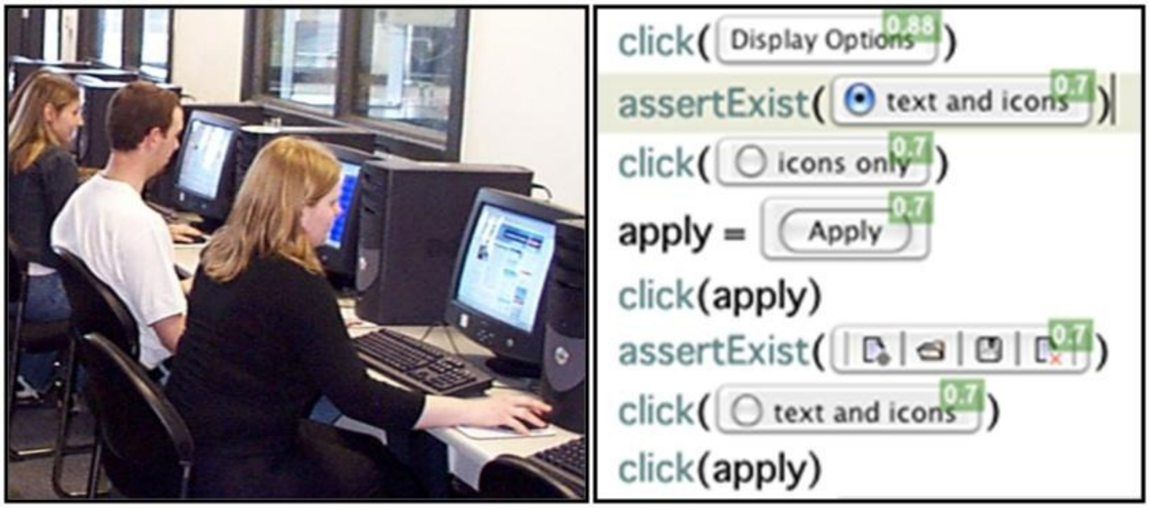
GUI Testing with Screenshots and Computer Vision

Quality Assurance (QA) testers are critical to the development of a GUI application. Working closely with both programmers and designers, QA testers make efforts to ensure the GUI application is correctly implemented by following the design specification. Without such efforts, there is no guarantee the usability promised by a good design is fully realized in the implementation.

However, GUI testing is a labor intensive task. Consider the following GUI behavior defined in a design specification of a video player: *click the button* ▶ *and it becomes* ⏸. To test if this behavior is correctly implemented, a tester must *look for* the "play" button on the screen, *click* on it, and *see* if it is replaced by the "pause" button. Every time this behavior needs to be tested again, the tester must manually repeat the same task all over again.

While GUI testers often toil in their tedious tasks, testers of non-GUI applications have been enjoying the convenience of tools to automate their tasks. For example, to test if the function call `addOne(3)` behaves correctly, a tester can write a script that makes this function call, followed by an assertion function call, such as `assert(addOne(3) == 4)`, to check if the result is equal to 4 and report an error if not. This script can be run automatically as many times as desired, which greatly reduces the tester's effort.

In this chapter, we present Sikuli Test, a new approach to GUI testing that uses screen-



```
click( Display Options 0.88 )
assertExist( ● text and icons 0.7 )
click( ○ icons only 0.7 )
apply = ( Apply 0.7 )
click(apply)
assertExist( 0.7 )
click( ○ text and icons 0.7 )
click(apply)
```

Figure 4-1: GUI testing (left) traditionally requires human testers to operate the GUI and verify its behavior visually. Our new testing framework allows the testers to write visual scripts (right) to automate this labor-intensive task.

shots and computer vision to help GUI testers automate their tasks. Sikuli Test enables GUI testers to write *visual* scripts using images to define what GUI widgets to be tested and what visual feedback to be observed. For example, to automate the task of testing the behavior of the video player described above, a tester can write the following script:

```
button = find(▶)
click(button)
assert button.exists(⏸)
assert not button.exists(▶)
```

When this script is executed, it will act like a robotic tester with eyes to *look for* the "play" button on the screen, *click* on it, and *see* if it is replaced by the "pause" button, as if the human tester is operating and observing the GUI him- or herself (Figure 4-1).

This chapter is outlined with the following sections.

Interview study with GUI testers We examine the limitations of current testing tools and suggest design requirements for a new testing framework.

Automation of visual assertion Based on the visual automation API provided by Sikuli Script [49], a set of visual assertion API is added to determine if expected outputs are shown or not. The extension of visual assertion fulfills the automation of GUI testing by using images for verifying outputs in addition to directing inputs.

Test-By-Demonstration Testers can interact with a GUI and record the actions they perform and visual feedback they see. Test scripts can be automatically generated to reproduce the actions and verify the visual feedback for testing purposes.

Support of good testing practices Features are introduced to support good testing practices including unit testing, regression testing, and test driven development.

Comprehensive evaluation We analyze the testability of a wide range of visual behavior based on five actual GUI applications. Also, we examine the reusability of test scripts based on two actual GUI applications evolving over many versions.

4.1 Interview Study

To guide the design and development of our new GUI testing tool, we conducted informal interviews with four professionals of GUI testing from academia and industry. Questions asked during the interviews were centered on three topics: current testing practices, use of existing tools, and experience with existing tools.

In terms of testing practices, we found most of our subjects are involved in the early design process to coordinate and formulate workable test plans to ensure quality and testability. Testing is performed frequently (often daily) on the core components. For example, underlying APIs are tested with simulated inputs and checked if they produce expected outputs. But testing the outward behavior of GUIs is less frequent, usually on major milestones by a lot of human testers. Some of them regularly apply good testing practices such as unit testing, regression testing, and test-driven development; but the scope of these practices is limited to the parts without GUI.

In terms of the use of testing tools, some have developed customized automation tools. They write scripts that refer to GUI objects by pre-programmed names or by locations to simulate user interactions with these objects. Some have been using existing tools such as Autoit [1], a BASIC-like scripting language designed to automate user interactions for Windows GUI applications.

In terms of experience with these tools, our subjects expressed frustration and described their experience as sometimes “painful”, “slow”, and “too much manual work.” Several problems with current automatic testing tools were identified by the subjects, which might explain this frustration. First, whenever the GUI design is modified and the positions of GUI components are rearranged, automatic tools based on the absolute position of components often fail and would actually “slow down the testing process” because of the need to modify the test scripts. Second, while automatic tools based on component naming may avoid this problem, many components simply can not or have not been named.

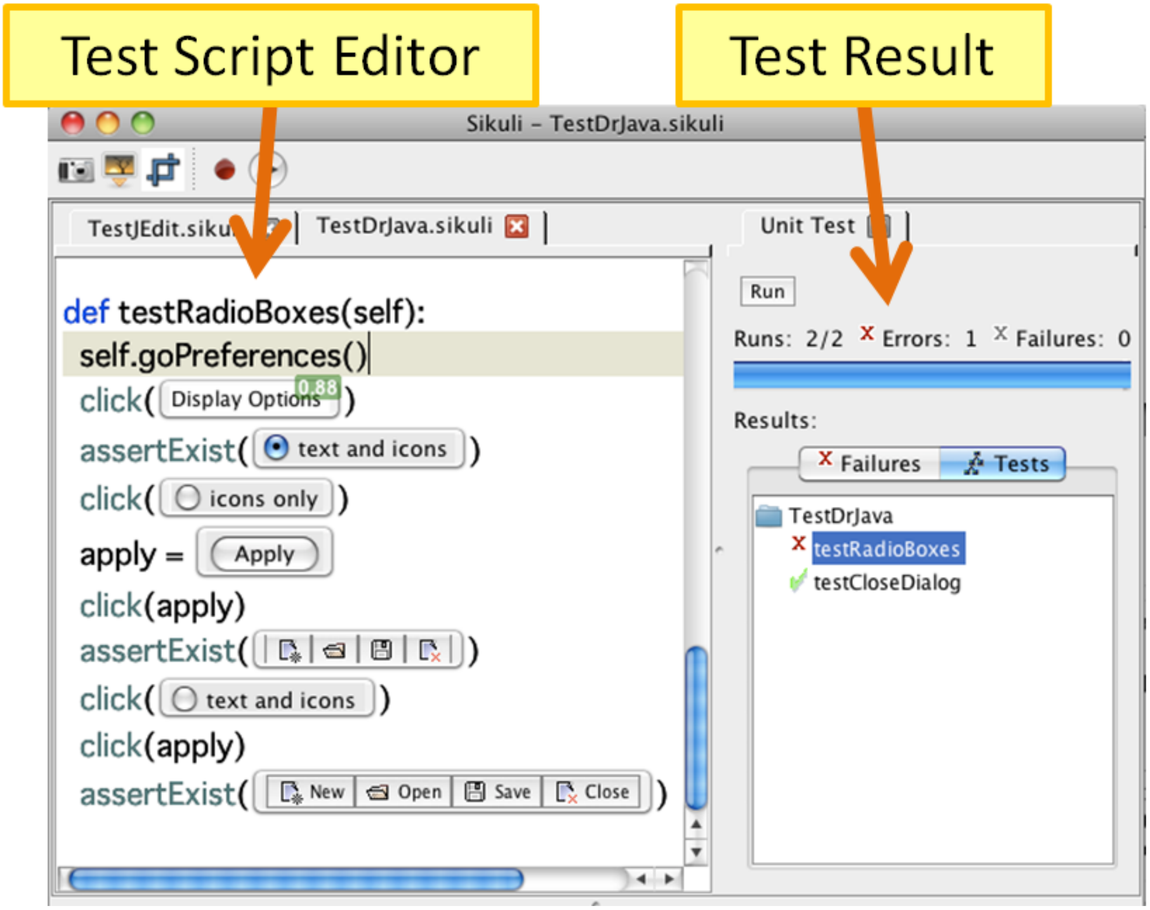
Based on the findings of this interview, we identified the following five design goals to guide the design and development of our new GUI testing tool:

- (G1) The tool should allow testers to write scripts to automate tests.
- (G2) The tool should not require testers to refer GUI components by names or by locations.
- (G3) The tool should minimize the instances when test scripts need to be modified due to design changes.
- (G4) The tool should minimize the effort of writing test scripts.
- (G5) The tool should support good testing practices such as unit testing, regression testing, and test-driven development.

4.2 Testing By Visual Automation

We present Sikuli Test, a testing framework based on computer vision that enables developers and QA testers to automate GUI testing tasks. Consider the following task description for testing a particular GUI feature:

> Click on the color palette button. Check if the color picking dialog appears.



```
def testRadioBoxes(self):
    self.goPreferences()
    click( Display Options 0.88 )
    assertExist( ● text and icons )
    click( ○ icons only )
    apply = Apply
    click(apply)
    assertExist( | | | | )
    click( ○ text and icons )
    click(apply)
    assertExist( New | Open | Save | Close )
```

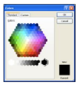
Runs: 2/2 ✗ Errors: 1 ✗ Failures: 0

TestDrJava
✗ testRadioBoxes
✓ testCloseDialog

Figure 4-2: Sikuli Test interface consists of a test script editor and an information panel summarizing the test result.

To carry out this test case, QA testers need to manually interact with the GUI and visually check if the outcome is correct. Using Sikuli Test, the testers can automate this process by converting the task description into an automation script. This script consists of action statements to simulate the interactions and assertion statements to visually verify the outcomes of these interactions. For example, the above task description can be easily translated into a test script as:

click( )

assertExist()

By taking this image-based scripting approach, Sikuli Test meets the first three design goals: it allows testers to write visual scripts to automate tests (G1), to refer to GUI objects by their visual representation directly (G2), and to provide robustness to changes in spatial arrangements of GUI components (G3). The details of how to write test scripts using action statements and assertion statements are given next.

4.2.1 Simulating Interactions using Action Statements

To simulate interactions involved in a test case, QA testers can write action statements using the Sikuli Script API, which is described in Chapter 3.

Since Sikuli Script is based on a full scripting language, Python, it is possible for QA testers to programmatically simulate a large variety of user interactions, simple or complex.

4.2.2 Verifying Outcomes using Visual Assertion Statements

Sikuli Test introduces two *visual assertion* functions. QA testers can include these functions in a test script to verify whether certain GUI interaction generates the desired visual feedback. These two assertion functions are:

`assertExist(image or string [, region])`

asserts that an image or string that should appear on screen or in a specific screen region

`assertNotExist(image or string [, region])`

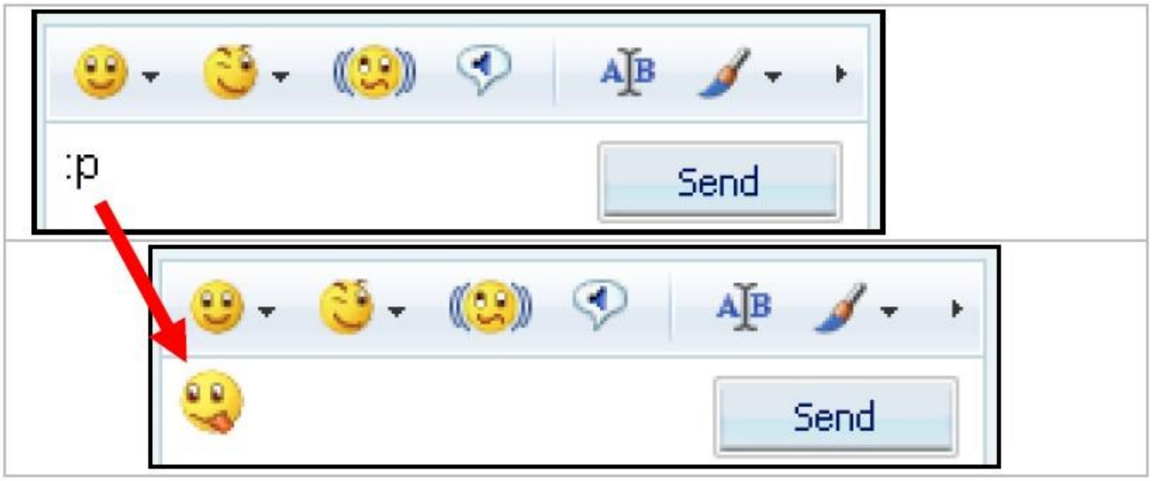
asserts that an image or a string should not appear on screen or in a specific screen region

The `image` is specified as URL or a path to an image file. It also can be captured by a screenshot tool provided in our Integrated Development Environment (IDE). When a string is specified, OCR (Optical Character Recognition) is performed to check if the specified string can be found in the screen region. The optional parameter `region` is specified as a rectangular area on the screen (i.e., x, y, width, height). If not specified, the entire screen is checked. Alternatively, the region can be specified as a second image, in which case the entire screen is searched for that image and the matching region is searched for the first image. Spatial operators such as *inside*, *outside*, *right*, *bottom*, *left*, and *top* can be further applied to a region object to derive other regions in a relative manner.

4.2.3 Examples

We present examples to illustrate how test scripts can be written to verify visual feedback.

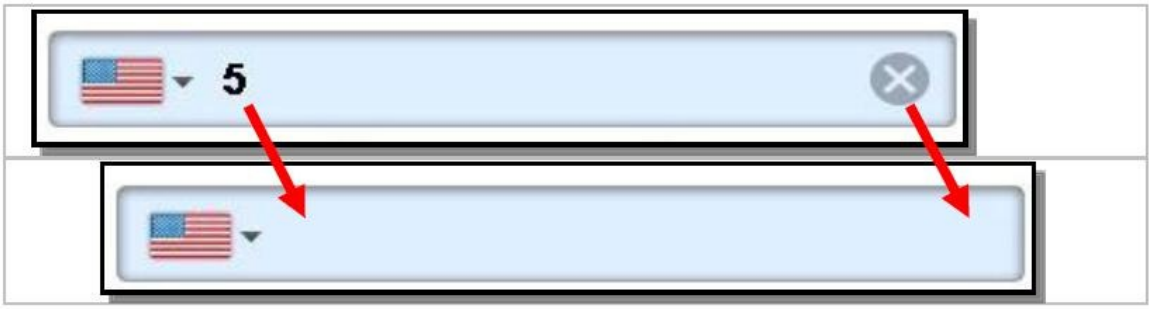
1. Appearance



```
type(":p")
assertExist(😛)
```

In some instant messengers, textual emoticons, e.g. smiley face :), are replaced by graphical representations automatically. This example shows how to test the appearance of the corresponding graphical face once the textual emoticon is entered in Windows Live Messenger.

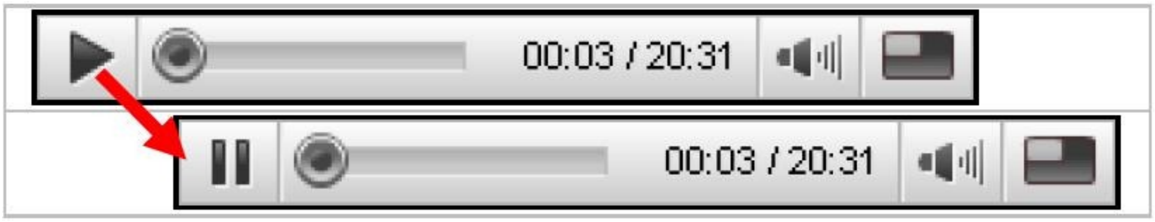
2. Disappearance



```
blueArea = find(▾ 5 ⊗)[0]
closeButton = ⊗
click(closeButton)
assertNotExist(closeButton, blueArea)
assertNotExist("5", blueArea)
```

In this example, the close button ⊗ is expected to clear the content of the text box as well as itself. Suppose the GUI is already in a state that contains a "5", at first we find the blue text box on the screen and store the matched region that has the highest similarity in *blueArea*. Then, after clicking the close button, two assertNotExist statements are used to verify the disappearance in the blue area.

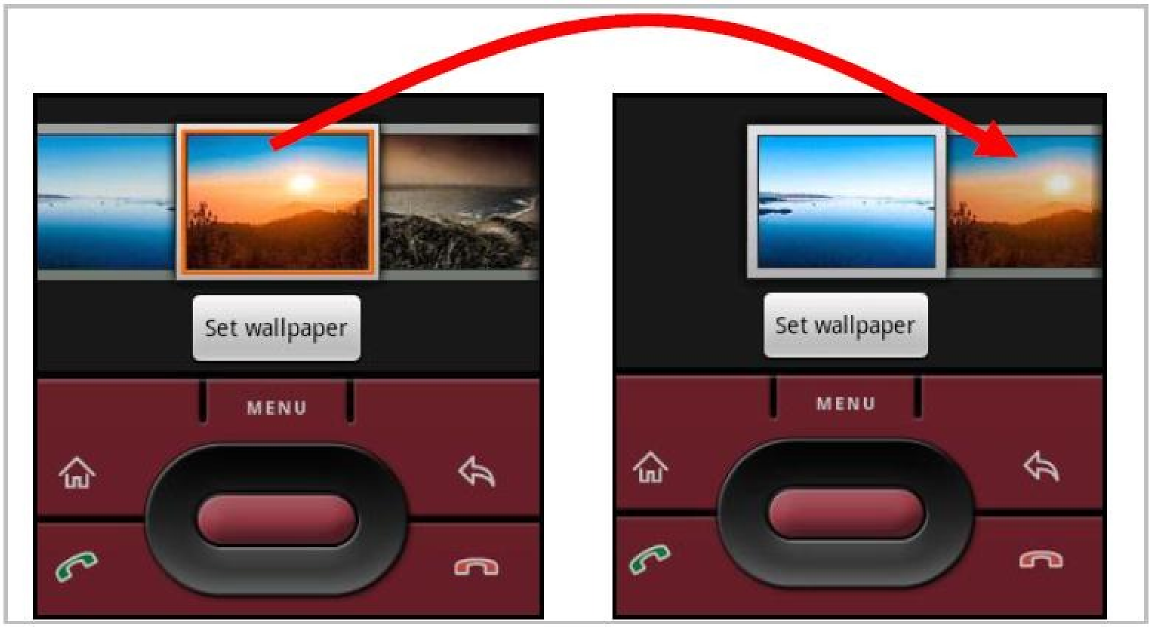
3. Replacement

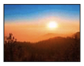
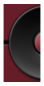


```
button = find(▶)
click(button)
assertExist(⏸, button)
assertNotExist(▶, button)
```

Typical media players have a toggle button that displays the two possible states of the player, playing or pause. In this example, we demonstrate a test case that tests the typical toggle button on youtube.com, a popular website of video collection. This script finds the play button first, and save its match region in the variable *button*. After clicking on the play button, all following assertions are restricted within that matched region in order to verify the replacement behavior.

4. Scrolling/Movement



```
sunset = 
old_x = find(()sunset)[0].x
click()
assert(find(()sunset)[0].x > old_x)
```

Since Sikuli Test is independent of any GUI platform, it also can be used to test mobile applications running on an emulator. This example shows how to test scrolling and movement on an Android emulator. This test case works by comparing the position of the target before and after an action that should move the target. After clicking on the left button, we expect the series of images to scroll rightward. Therefore, the new x coordinate should be larger than the old one. We choose the image of sunset to be the target. Its x coordinate that derived from the most similar match of *find()* is stored in *old_x*. After clicking on the left button, its new x coordinate derived from *find()* again is compared with *old_x* for verifying the correctness of the implementation.

4.3 Testing By Demonstration

Sikuli Test provides a record-playback utility that enables QA testers to automate GUI testing by demonstration. The operation of a GUI can be described as a cycle consisting of actions and feedback. Given a test case, the testers follow the given actions to operate a GUI, and verify if the visual feedback is the same as expected. If so, they proceed to do the next actions and to verify further feedback.

With the record-playback mechanism, the testers can demonstrate the interactions involved in the test case. The actions as well as the screen are recorded and translated into a sequence of action and assertion statements automatically. The action statements, when being executed, can replicate the actions, as if the testers are operating the GUI themselves. The assertion statements can verify if the automated interactions lead to the desired visual feedback, as if the testers are looking at the screen themselves.

The test-by-demonstration capability of Sikuli Script satisfies the design goal of minimizing the effort needed to write test scripts (G4). Details of how demonstration is recorded and how actions and assertions are automatically generated from the recorded demonstration will be given next.

4.3.1 Recording Demonstration

As QA testers demonstrate a test case, a recorder is running in the background to capture the actions they perform and the visual feedback they see. To capture actions, the recorder hooks into the global event queue of the operating system to listen for input events related to the mouse and the keyboard. The list of mouse events recorded includes *mouse_down, mouse_up, mouse_move*, and *mouse_drag*. Each mouse event is stored with the cursor location (x, y) and the state of buttons. The keyboard events recorded include *key_down* and *key_up*, stored together with key codes. All events include a *timestamp* that is used to synchronize with the screen recording. To capture screens, the recorder grabs the screenshot of the entire screen from the video buffer in the operating system periodically. In our prototype, the recording can be done at 5 fps at a resolution of 1280x800 on a machine with 2Ghz CPU and 2GB memory.

4.3.2 Generating Action Statements

Given a series of screen images and input events captured by the recorder, action statements can be generated to replay the interactions demonstrated by the testers. For example, a single mouse click recorded at time t at location (x, y) can be directly mapped to *click(I)* where I is the image of the GUI component that was clicked. The image I can be obtained by cropping a region around (x, y) from the screen image captured at time $t-1$ right before the click event.

The timing to capture the screen images could be more complicated if there are multiple targets involved in one action statement, such as dragDrop. As a user interact with GUI components, some visual feedback that changes the look of the GUI may be triggered by the user's mouseover events. Therefore, both the images of the source and the target should be captured before the drag-and-drop begins.

In our current implementation, a constant-size (80x50) region around the input location is cropped to represent the target GUI component receiving the input. Even though the region may not necessarily fit the target component perfectly, often it contains enough pixels to uniquely identify the component on the screen. If ambiguity arises, the user can adjust the cropping area to include more pixels of the component or the context to resolve the ambiguity at any time.

Some input events may need to be grouped into a single action statement. For example, two consecutive mouse clicks in a short span of time is mapped to *doubleClick()*. Keyboard typing events can be clustered to form a string and mapped to *type(string)*. A *mouse_down* event at one location followed by a *mouse_up* event at another location can be mapped to *dragDrop(I,J)* where I and J denote the images extracted from the locations of the two mouse events respectively.

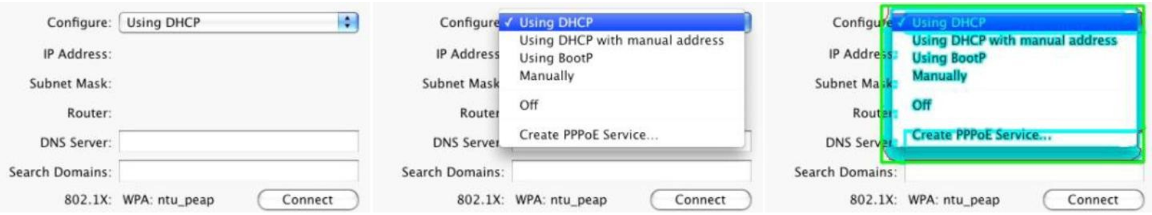
4.3.3 Generating Assertion Statements

Assertion statements can also be automatically derived from the screen images captured during the demonstration. We developed and implemented a simple vision algorithm to accomplish this. We assume any salient change between the two images is very likely to be the visual feedback caused by an input event. Our algorithm compares the screen images I_t and I_{t+1} where t is the time of a recorded input event, and identifies pixels that are visually different. It then clusters the changed pixels in close proximity and merges them into the same group. Each group of pixels would probably correspond to the same GUI component. Finally, it computes a bounding rectangle around each group and obtains a cropped image containing the visual feedback of each GUI component visually affected by the input event. If the cropped boundaries are bad, the user can adjust the cropping area anytime on the recorded images.

An assertion statement that can be later used to check the presence of the visual feedback can be generated with this algorithm. Figure 4-3 shows an example of deriving the visual feedback where a drop-down box is opened by clicking. Often, more than one GUI component can exhibit visual feedback as the result of a single input event. In this case, our algorithm results in a compound assertion statement including multiple cropped image regions. For example, Figure 4-4 shows a dialog box with a checkbox that can be used to enable several GUI components at once. Checking this checkbox will cause all previously greyed out components in a panel to regain their vivid colors.

An optional step for the tester to increase the reliability of the automatic visual feedback detector is to provide hints to where it should look for the visual feedback. After performing an interaction and before moving on to the next, the tester can move the mouse cursor to the area where the visual feedback has occurred and press a special key, F5, to trigger a hint. The detector can use the location of the cursor to extract the relevant visual feedback more reliably and generates an appropriate assertion statement.

While we can identify many cases in which visual assertion statements can be created automatically in this manner, there remain a few challenges. First, periodic changes in the desktop background, such as those related to the system clock or the wireless signal indi-



Configure: Using DHCP

802.1X: WPA: ntu_peap

Figure 4-3: An example of taking the difference between two screens to derive the visual feedback automatically

cator, may be inadvertently detected but irrelevant to the GUI to be tested. One solution would be to ask the testers to specify the boundary of the GUI beforehand so that background noises can be filtered out. Second, certain actions might take longer to obtain any visual feedback; the screen image captured immediately after the action might not contain the visual feedback. One solution would be to wait until a significant change is detected. Third, some visual feedback may involve animation spanning several frames, for example, a large window appearing in a blind-rolling-down fashion. One solution would be to wait until the screen has stabilized and focus only on the final visual feedback. However, while it is possible to test the final feedback, testing the intermediate steps of an animation can still be unreliable, because it is difficult to synchronize between the frames sampled during the demonstration time and those sampled during the test time.

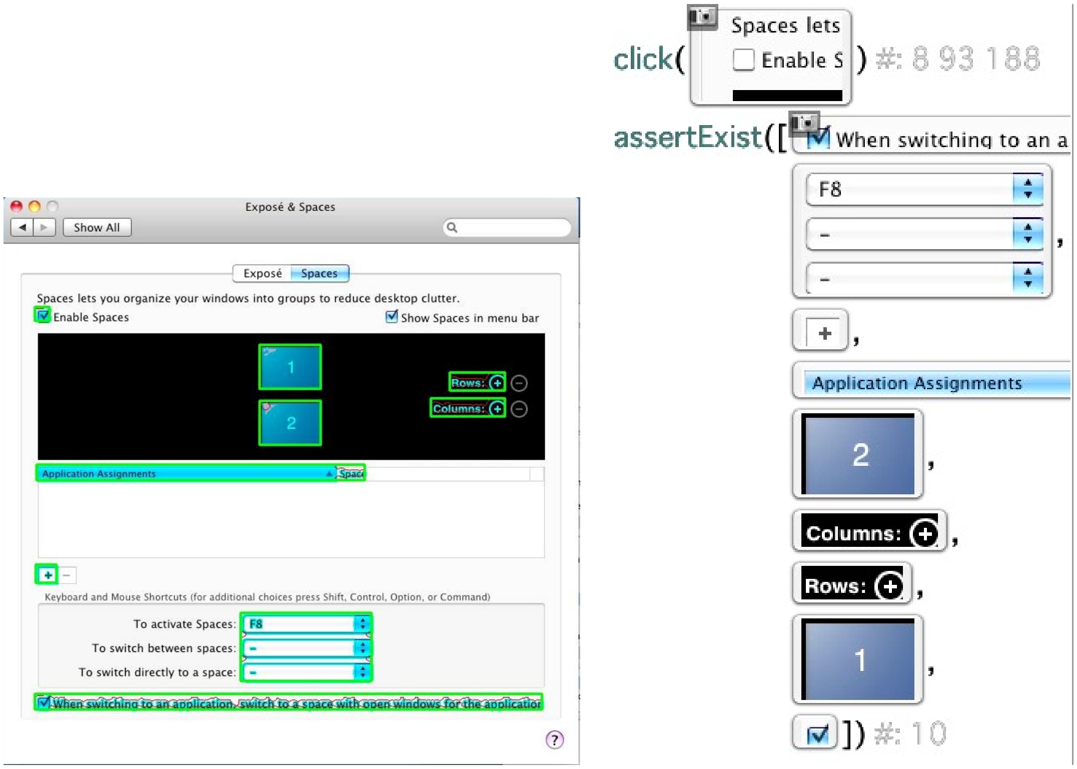
4.4 Supporting Good Testing Practices

Sikuli Test comes with a set of features to help GUI developers and QA testers engage in good testing practices such as unit testing, regression testing, and test-driven development, satisfying the last design goal (G5).

4.4.1 Unit Testing

When a GUI is complex, to make sure it is tested thoroughly requires a systematic approach. One such approach is to break the GUI down into manageable units, each of which targets a particular part, feature, or scenario. This approach is known as *unit testing*.

To support unit testing for GUI, Sikuli Test draws many design inspirations from JUnit,



Exposé & Spaces

Show All

Exposé | Spaces

Spaces lets you organize your windows into groups to reduce desktop clutter.

☑ Enable Spaces ☑ Show Spaces in menu bar

Rows: ⊕ ⊖

Columns: ⊕ ⊖

Application Assignments | Space

+ −

Keyboard and Mouse Shortcuts (for additional choices press Shift, Control, Option, or Command)

To activate Spaces: F8

To switch between spaces: –

To switch directly to a space: –

☑ When switching to an application, switch to a space with open windows for the application

```
click( Spaces lets □ Enable S ) #: 8 93 188
assertExist([ ☑ When switching to an a
             F8 – – ,
             + ,
             Application Assignments
             2 ,
             Columns: ⊕ ,
             Rows: ⊕ ,
             1 ,
             ☑ ]) #: 10
```

Figure 4-4: Example of automatic generation of assertion statements from detected visual feedback.

a popular unit testing framework for Java programming:

1. Testers can define each test as a function written in Python. Every test function is meant to be run independently without relying on the side-effects of another test function. For example, after testing the *exit* button, which has the side effect of closing the application, no more tests can be run unless the GUI is restarted. Therefore, to run every test independently, Sikuli Test provides two functions *setUp()* and *tearDown()* that can be overridden by testers to set up and to clean up the testing environment. A typical way to achieve the independence is always starting the GUI in a fresh configuration before running a test.

2. Testers can define common action functions to automatically advance the GUI to a particular state in order to run certain tests only relevant in that state. Common action functions can be shared among all test cases in the same script to reduce redundant code and to prevent future inconsistency. For example, suppose the *Save Dialog*

box is relevant to several test cases, the tester can write a common action function to open the Save Dialog that contains a `click()` on the *File* menu followed by another `click()` on the *Save* item. On the other hand, testers can also define shared assertion functions to verify the same visual feedback that are derived from different actions. For example, the appearance of a *save* dialog box can be caused by a hotkey Ctrl-S, by a icon on the toolbar, or by the Save item in the File menu; all could be verified by `assertSaveDialog()`.

3. Testers can run a test script and monitor the progress as each test function in the script is run. They can see the summary showing whether each test has succeeded or failed as well as the total number of successes and failures.

4. When errors are found, testers can communicate the errors to programmers effectively. On the one hand, testers are encouraged to assign each test function a meaningful name, such as *test_click_play_button*. On the other hand, the images embedded in each function make it visually clear which GUI components and what visual feedback are involved in the errors.

4.4.2 Regression Testing

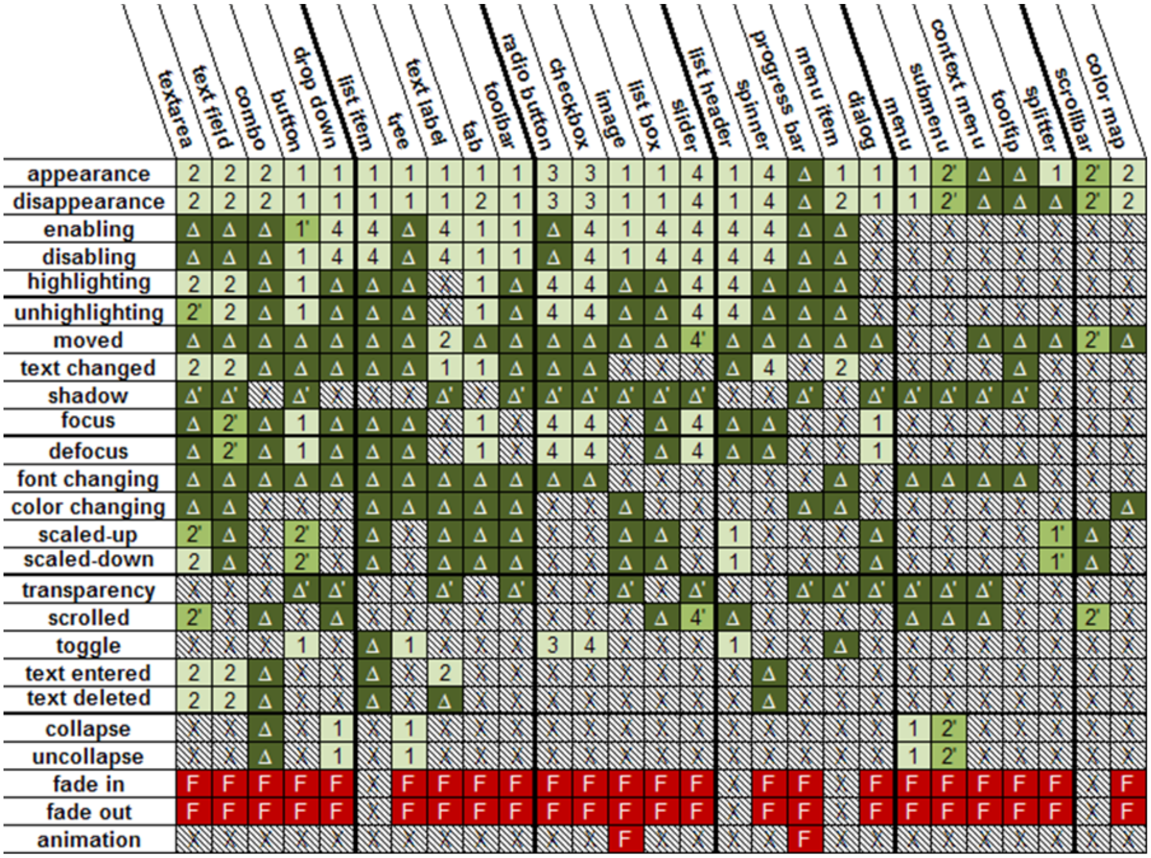
When a new feature is implemented, in addition to verifying whether the implementation is correct, it is equally important to ensure that it does not break any existing feature that used to be working. This practice is often known as *regression testing* in software engineering. Many software projects use daily builds to automatically check out and compile the latest development version from the version control system. The daily build is tested by automated unit testing suites to validate the basic functionality. However, because of the weaknesses of automatic testing tools for GUI, current regression testing process is limited to work only on internal components but not on GUI. Therefore, regression testing becomes a tedious practice that requires QA testers to manually repeat the same set of tests whenever there is a modification to the GUI.

Sikuli Test is a labor-saving and time-saving tool enabling QA testers to automate regression testing. Using Sikuli Test, the testers only need to program test cases once and those test cases can be repeatedly applied to check the integrity of the GUI. To show the feasibility of Sikuli Test for supporting regression testing, an evaluation will be given later.

4.4.3 Test-Driven Development

While our testing framework is originally designed for QA testers, it can be used by both GUI designers and programmers during the development process. In large GUI projects where the separation between design and implementation is clearer, designers can create test cases based on design illustrations or high-fidelity prototypes. For example, a designer can use a graphic editor such as Photoshop to create a picture illustrating the GUI's desired visual appearance. Based on this picture, the designer can crop representative images of operable GUI components such as buttons to compose action statements. The designer can also graphically illustrate the expected visual feedback when these GUI components are operated. Again, this graphical illustration can be used directly in assertion statements. Test cases can be created and handed to programmers to implement the GUI's outward visual behavior. These test cases will initially fail because none of the desired visual behavior has been implemented yet. As more features are implemented, more test cases can be passed. When all the test cases are passed, the implementation is not only complete but also thoroughly tested. This practice is often known as *test-driven development*, which has been widely adopted by non-GUI development projects. Our visual testing framework initiates an opportunity for GUI designers and programmers to engage in this good practice of software engineering.

Even in small projects when a programmer often doubles as a designer and a tester, test-driven development can still be practiced. For example, given a design specification, a program can create the skin of a GUI without any functionality using a Rapid Application Development (RAD) tool. Then, before the actual implementation, the programmer can take the screenshots of the skin to write test cases and start writing GUI code to pass these test cases.



	textarea	text field	combo	button	drop down	list item	tree	text label	tab	toolbar	radio button	checkbox	image	list box	slider	list header	spinner	progress bar	menu item	dialog	menu	submenu	context menu	tooltip	splitter	scrollbar	color map
appearance	2	2	2	1	1	1	1	1	1	1	3	3	1	1	4	1	4	Δ	1	1	1	2'	Δ	Δ	1	2'	2
disappearance	2	2	2	1	1	1	1	1	2	1	3	3	1	1	4	1	4	Δ	2	1	1	2'	Δ	Δ	Δ	2'	2
enabling	Δ	Δ	Δ	1'	4	4	Δ	4	1	1	Δ	4	1	4	4	4	4	Δ	Δ	X	X	X	X	X	X	X	X
disabling	Δ	Δ	Δ	1	4	4	Δ	4	1	1	Δ	4	1	4	4	4	4	Δ	Δ	X	X	X	X	X	X	X	X
highlighting	2	2	Δ	1	Δ	Δ	Δ	X	1	Δ	4	4	Δ	Δ	4	4	Δ	Δ	Δ	X	X	X	X	X	X	X	X
unhighlighting	2'	2	Δ	1	Δ	Δ	Δ	X	1	Δ	4	4	Δ	Δ	4	4	Δ	Δ	Δ	X	X	X	X	X	X	X	X
moved	Δ	Δ	Δ	Δ	Δ	Δ	Δ	2	Δ	Δ	Δ	Δ	Δ	Δ	4'	Δ	Δ	Δ	Δ	Δ	X	X	Δ	Δ	Δ	2'	Δ
text changed	2	2	Δ	Δ	Δ	Δ	Δ	1	1	Δ	Δ	Δ	X	X	X	Δ	4	X	2	X	X	X	X	Δ	X	X	X
shadow	Δ'	Δ'	X	Δ'	X	X	X	Δ'	X	Δ'	Δ'	Δ'	Δ'	Δ'	Δ'	X	X	Δ'	X	Δ'	Δ'	Δ'	Δ'	Δ'	X	X	X
focus	Δ	2'	Δ	1	Δ	Δ	Δ	X	1	X	4	4	X	Δ	4	Δ	Δ	X	X	1	X	X	X	X	X	X	X
defocus	Δ	2'	Δ	1	Δ	Δ	Δ	X	1	X	4	4	X	Δ	4	Δ	Δ	X	X	1	X	X	X	X	X	X	X
font changing	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	Δ	X	X	X	X	X	X	Δ	X	Δ	Δ	Δ	Δ	X	X	X
color changing	Δ	Δ	X	X	X	Δ	Δ	Δ	Δ	Δ	X	X	Δ	X	X	X	X	Δ	Δ	X	X	X	X	X	X	X	Δ
scaled-up	2'	Δ	X	2'	X	Δ	X	Δ	Δ	Δ	X	X	Δ	Δ	X	1	X	X	X	Δ	X	X	X	X	1'	Δ	X
scaled-down	2	Δ	X	2'	X	Δ	X	Δ	Δ	Δ	X	X	Δ	Δ	X	1	X	X	X	Δ	X	X	X	X	1'	Δ	X
transparency	X	X	X	Δ'	Δ'	X	X	Δ'	X	Δ'	X	X	Δ'	X	Δ'	X	X	Δ'	Δ'	Δ'	Δ'	Δ'	Δ'	X	X	X	X
scrolled	2'	X	Δ	X	Δ	X	X	X	X	X	X	X	X	Δ	4'	Δ	X	X	X	X	Δ	Δ	Δ	X	X	2'	X
toggle	X	X	X	1	X	Δ	1	X	X	X	3	4	X	X	X	1	X	X	Δ	X	X	X	X	X	X	X	X
text entered	2	2	Δ	X	X	Δ	X	2	X	X	X	X	X	X	X	X	Δ	X	X	X	X	X	X	X	X	X	X
text deleted	2	2	Δ	X	X	Δ	X	Δ	X	X	X	X	X	X	X	X	Δ	X	X	X	X	X	X	X	X	X	X
collapse	X	X	Δ	X	1	X	1	X	X	X	X	X	X	X	X	X	X	X	X	X	1	2'	X	X	X	X	X
uncollapse	X	X	Δ	X	1	X	1	X	X	X	X	X	X	X	X	X	X	X	X	X	1	2'	X	X	X	X	X
fade in	F	F	F	F	F	X	F	F	F	F	F	F	F	F	F	X	F	F	X	F	F	F	F	F	F	X	F
fade out	F	F	F	F	F	X	F	F	F	F	F	F	F	F	F	X	F	F	X	F	F	F	F	F	F	X	F
animation	X	X	X	X	X	X	X	X	X	X	X	X	F	X	X	X	X	F	X	X	X	X	X	X	X	X	X

Table 4.1: The testability of GUI visual behavior under Sikuli Test. The numbers (1 to 4) indicate the combination of the widget and the visual behavior can be tested with Sikuli Test in the corresponding application. The triangles △ indicate theoretically testable, and the red *F*s mean not testable by Sikuli Test. The rest of the cells marked with an *X* indicates they are rarely paired together.

4.5 Evaluation

To evaluate Sikuli Test, we performed testability analysis—how diverse the visual behavior GUI testers can test automatically, and reusability analysis—how likely testers can reuse a test script as a GUI evolves.

4.5.1 Testability Analysis

We performed testability analysis on a diverse set of visual behavior. Each visual behavior can be defined as a pairing of a GUI widget and a visual effect rendered on it. We considered 27 common widgets (e.g., button, check box, slider, etc.) and 25 visual effects (e.g., appearance, highlight, focus, etc.). Out of the 675 possible pairings, we identified 368 to be valid, excluding those that are improbable. We began the analysis by applying Sikuli Test to test the visual behavior exhibited by four real GUI applications (i.e., 1: Capivara, 2: jEdit, 3: DrJava, and 4: System Preferences on Mac OS X).

For each pair of a GUI widget and a visual effect, we wrote a script for it using Sikuli Test to confirm if it is testable. For example, say we would like to know if "text changed" in a text field is testable, we first found an application that has this combination of visual behavior, which is (2) jEdit in our experiment. Then we wrote a script, which changed the text in a text field in jEdit and used an assertExists statement to verify it. If the script can successfully test this change, we say this pair is testable.

Some pairs of visual behavior are rarely combined together. We call them *improbable*. For example, the pair of scrolling bars and font changing is improbable, because there is even no fonts or text in scrolling bars. Therefore, this pair of visual behavior is unlikely to be combined together in most GUI applications.

Table 4.1 summarizes the result of the testability analysis. Each cell corresponds to a visual behavior. Out of 368 valid visual behaviors, 139 (indicated by the number of the application used to be tested) are *empirically testable*, visual behavior was found in the four applications and could be tested; 181 (indicated by a triangle △) are *theoretically testable*, visual behavior was not found in the four applications but could be inferred from the testability of other similar visual behavior; and 48 (indicated by an "F") are *not testable* by Sikuli Test. In addition to these valid visual behaviors, there are 307 rarely paired improbable visual behaviors indicated by an "X".

As can be seen, the majority of the valid visual behavior considered in this analysis can be tested by Sikuli Test. However, complex visual behavior such as those involving animations (i.e., fading, animation) are currently not testable, which is a topic for future work.

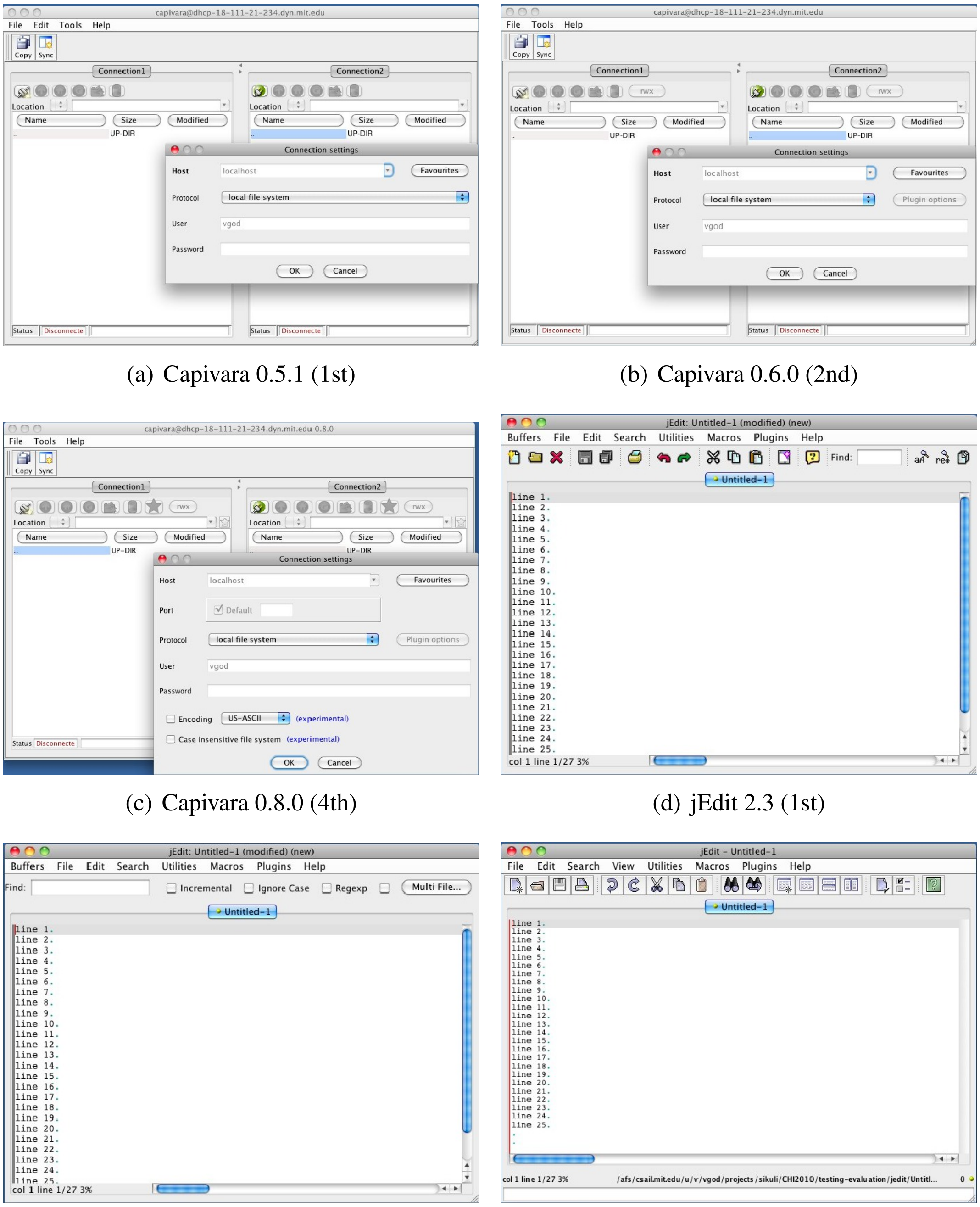
4.5.2 Reusability Analysis

We performed reusability analysis of test scripts based on two real GUI applications: Capivara, a file synchronization tool, and jEdit, a rich-text editor. These two applications were selected from the popular downloads on SourceForge.net with two criteria: it must have a rich set of GUI widgets, and it must have at least 5 major releases available for download.

First, we focused on the two earliest versions that can be downloaded of the two applications. For Capivara, we chose versions 0.5.1 (Apr. '05) and 0.6 (June '05) (Figure 4-5 a,b). For jEdit, we chose versions 2.3 (Mar. '00) and 2.41 (Apr. '00) (Figure 4-5 d,e). Since there were modifications to the user interface between these two versions, we were interested in whether test cases written for the first version can be applied to the second version to test the unmodified parts of the application. We created 10 and 13 test cases for Capivara and jEdit respectively. Most of the test cases were created using the test-by-demonstration tool, while some required manual adjustments such as giving hints and removing excess contexts from the detected visual feedback. Examples of the test cases can be seen in Figure 4-6.

Table 4.2 summarizes our findings. These two tables include the first two versions, plus a later version that showed drastic change in the GUI for Capivara and jEdit respectively. The column of the first version shows how each test case is made: *A* denotes automatically generated, *AM* denotes automatically generated with some modifications, such as giving hints and removing excess contexts from the detected visual feedback, and *M* denotes manually written. Each column of the other two versions shows the result of each test case at the version: *P* denotes passed, whereas *F1* - *F5* denote failure. (The cause of each failure will be explained later.)

Between the first two versions of Capivara, we observed one modification to the UI: the size limitation of the panel splitter was different. Thus, we only needed to update 1 of the 10 original test cases to reflect this modification. In other words, we were able to apply the other 9 test cases against the second version to test the correctness of unmodified features. Similarly, in the case of jEdit, we observed 3 modifications among the features covered by the original 13 test cases. Again, we were able to apply the remaining 10 test cases against


capivara@dhcp-18-111-21-234.dyn.mit.edu
File Edit Tools Help
Copy Sync
Connection1
Connection2
Location
Name Size Modified
UP-DIR
Connection settings
Favourites
OK Cancel
Status Disconnecte
capivara@dhcp-18-111-21-234.dyn.mit.edu
File Tools Help
rwx
Plugin options
capivara@dhcp-18-111-21-234.dyn.mit.edu 0.8.0
Port
(experimental)
jEdit: Untitled-1 (modified) (new)
Buffers File Edit Search Utilities Macros Plugins Help
Find:
Untitled-1
col 1 line 1/27 3%
Incremental Ignore Case Regexp Multi File...
jEdit - Untitled-1
File Edit Search View Utilities Macros Plugins Help
col 1 line 1/27 3%
/afs/csail.mit.edu/u/v/vgod/projects/sikuli/CHI2010/testing-evaluation/jedit/Untitl...

Host localhost
Protocol local file system
User vgod
Password

(a) Capivara 0.5.1 (1st)

Host localhost
Protocol local file system
User vgod
Password

(b) Capivara 0.6.0 (2nd)

Host localhost
Port ☑ Default
Protocol local file system
User vgod
Password
□ Encoding US-ASCII
□ Case insensitive file system

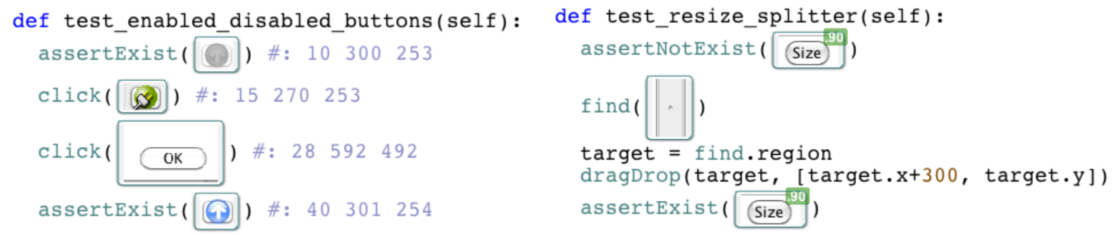
(c) Capivara 0.8.0 (4th)

(d) jEdit 2.3 (1st)

(e) jEdit 2.4.1 (2nd)

(f) jEdit 2.6 (4th)

Figure 4-5: GUI applications used to evaluate the reusability of Sikuli Test scripts as these applications evolve. Between (a) and (b), there is only one minor change in the connection settings dialog (a new button below Favourites), but the dialog has significant changes in (c). As for jEdit, between (d) and (e), a major change is the disappearance of the tool bar. However, it comes back with a different style in (f).



```
def test_enabled_disabled_buttons(self):
  assertExist() #: 10 300 253
  click() #: 15 270 253
  click(OK) #: 28 592 492
  assertExist() #: 40 301 254
```

(a) Example of an automatically generated test case

```
def test_resize_splitter(self):
  assertNotExist(Size .90)

  find()

  target = find.region
  dragDrop(target, [target.x+300, target.y])
  assertExist(Size .90)
```

(b) Example of a manual written test case

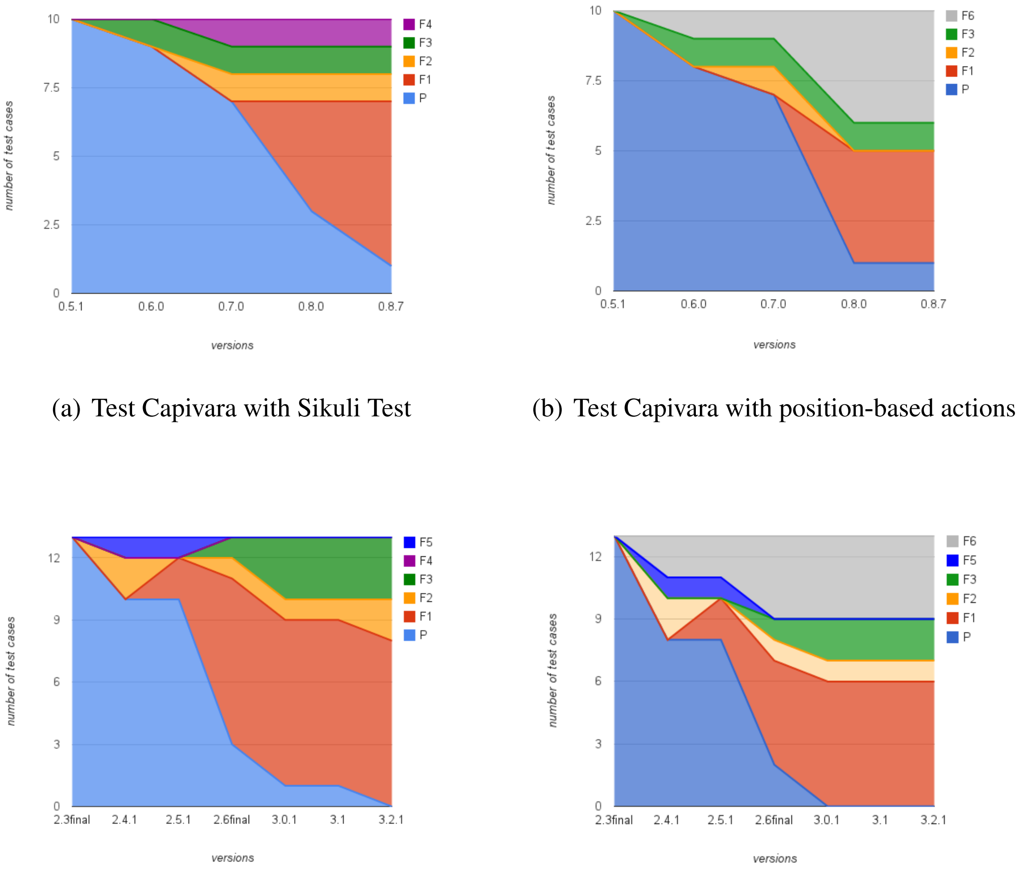
Figure 4-6: Example test cases for Capivara

the second version.

Next, we examined the long-term reusability of test cases as the applications undergo multiple design changes. For Capivara, we considered two additional major versions: 0.7.0 (Aug. ’05) and 0.8.0 (Sep. ’06), whereas for jEdit, we considered five more: 2.5.1 (Jul. ’00), 2.6final (Nov. ’00), 3.0.1 (Jan. ’01), 3.1 (Apr. ’01), and 3.2.1 (Sep. ’01). We tested whether each of the *original* test cases was still reusable to test the later versions and for those no longer reusable, identified the causes.

Figure 4-7 summarizes our findings. To show the reusability of the test cases, we arranged each version across the horizontal axis. For each version, the height of the baseline region (blue) indicates the number of the original test cases still being reusable for that version. This region exhibits a downward slope toward the direction of the newer versions, reflecting the fact that fewer and fewer of the original test cases remained applicable. The sharpest drop-off can be observed at version 0.8.0 for Capivara (Figure 4-5.c) and at 2.6final for jEdit (Figure 4-5.C), which can be attributed to the change of major design in these versions. The lesson that can be drawn from this observation is that as long as the design of a GUI evolve incrementally, as often the case, a significant number of test cases can be reusable, which is important for supporting regression testing.

Also, we identified five major causes for a test case to become unusable: (F1) change in the visual style, e.g. skin, size, font, etc.; (F2) removal of the action component, e.g. a button or a checkbox to be clicked; (F3) removal of the expected visual feedback, e.g. a dialog or some text appears; (F4) change in the surrounding of the target components; and (F5) change in internal behavior.



(a) Test Capivara with Sikuli Test

(b) Test Capivara with position-based actions

(c) Test jEdit with Sikuli Test

(d) Test jEdit with position-based actions

Figure 4-7: Long-term regression testing for Capivara and jEdit. (a) and (c) are tested with Sikuli Test, while (b) and (d) are done with position-based actions. P denotes the test was passed, and F1 to F6 are six different causes of failures: (F1) change in the visual style, e.g. skin, size, font, etc.; (F2) removal of the action component; (F3) removal of the expected visual feedback; (F4) change in the surrounding of the target components; (F5) change in internal behavior; and (F6) change of widget position (only occurred in position-based tests).

Test Cases of Capivara	(1st) 0.5.1	(2nd) 0.6.0	(4th) 0.8.0
connection-setting-cancel	A	P	P
connection-setting-ok	A	P	P
new-host-in-favorites	AM	P	F1
text-changed-in-status-and-tab	A	P	F1
menu-exit-dialog	AM	P	F2
toolbar-sync-dialog	A	P	P
name-size-column-in-listbox	A	P	F1
menu-options-tree	AM	P	F4
enabled-disabled-buttons	AM	P	F1
splitter-resize	M	F3	F3

Test Cases of jEdit	(1st) 2.3final	(2nd) 2.4.1	(4th) 2.6final
textarea-add-del-by-key	AM	P	F1
textarea-add-del-by-menu	AM	P	F1
new-tab-by-key	A	P	P
new-tab-by-menu	AM	P	P
new-tab-by-toolbar	AM	F2	F1
find-by-key	AM	P	F1
find-by-menu	AM	P	F1
find-by-toolbar	AM	P	F2
textfield-on-toolbar	AM	F5	F3
toolbar-print-dialog	A	F2	F1
menu-submenu	AM	P	P
scroll-textarea	M	P	F1
quit-cancel	A	P	F1

Table 4.2: Test cases created for the first version automatically (A), semi-automatically (AM) or manually (M) and their reusability (Pass or Fail) in subsequent versions (2nd and 4th).

Each cause of test failures is represented in the figure as one of the colored regions above the baseline region, with its height indicating the number of unusable test cases attributed to it. As can be expected, the most dominant cause is change in visual style (F1, orange), since our testing framework is largely driven by high-level visual cues. One surprising observation is an unusual upward slope of F2 occurred at jEdit 2.5.1, indicating that test cases that were not reusable in the previous version became reusable. Upon close examination, we found that toolbar icons were removed at 2.4.1 but reintroduced at 2.5.1, making the test cases targeting toolbar icons reusable again. While such reversal of GUI design is rare in practice, when it does happen, Sikuli Test is able to capture it.

To compare the performance of Sikuli Test with existing position-based methods (i.e. locating widget using fixed coordinates in the scripts instead of using screenshots), an extra set of experiments are done by replacing each screenshot in the action statements with the coordinate of the center of the location where the screenshot is taken. Figure 4-7 (b) and (d) show the result of this experiment, where F6 represents the failures caused by the change of widgets' location. This comparison shows that Sikuli Test effectively reduces the failures caused by the fixed-position method and extends the life of the test cases.

4.6 Conclusion

We presented Sikuli Test, a new approach to GUI testing using computer vision. Besides meeting the five design goals identified in an interview study with GUI testers, Sikuli Test offers three additional advantages:

1. **Readability of test cases:** The semantic gap between the test scripts and the test tasks automated by the scripts is small. It is easy to read a test script and understand what GUI feature the script is designed to test.

2. **Platform independence:** Regardless of the platform a GUI application is developed on, Sikuli Test can be used to test the GUI's visual feedback. We have shown the examples of test scripts written to test traditional desktop GUI applications on Windows and Mac OS X, as well as Web applications in a browser and mobile applications in an Android emulator. Even though Sikuli Test is not designed to let users write scripts once and use them across multiple platforms, it is still possible to do so as long as the appearance of the applications looks the same.

3. **Separation of design and implementation:** Test cases can be generated by designers and handed to programmers to implement features that must pass the test cases, to eliminate the biases that may arise when programmers are asked to test their own implementation.

However, Sikuli Test currently has two major limitations that can be improved upon in the future. First, while Sikuli Test can assert what visual feedback is expected to appear or to disappear, it is unable to detect unexpected visual feedback. For example, if a programmer accidentally places a random image in a blank area, it is an undetectable error since no one would have anticipated the need to test that area with assertions. One solution would be to run the visual feedback detector at the test time to see if there is any detected visual feedback not covered by an assertion statement. Second, Sikuli Test is designed to test a GUI's outward visual feedback and is thus unable to test the GUI's internal functionalities. For example, while Sikuli Test can check if a visual feedback is correctly provided to the user who clicks the save button, it does not know if the file is indeed saved. One solution would be to treat Sikuli Test not as a replacement of but a complement to an existing testing tool. Together they make sure both the outward feedback and inward functionalities of a GUI can be sufficiently tested, a task neither can accomplish alone.

Chapter 5

Deep Shot

The landscape of personal computing has shifted from one computer per user to multiple heterogeneous devices per user [13]. To carry out an everyday task, such as finding a restaurant for dinner, a user often switches from one device to another according to the situation. For example, a user has looked up the directions to the restaurant on her PC at home but then redoes the search on her phone for navigation in her car. A recent study found that this and other common tasks, such as email and web browsing, were the source of the most frustration while switching between different devices [24].

The lack of tool support for migrating tasks across devices has also been pointed out by several previous studies. A survey [35] conducted in 1997 showed that 62.9% of people stated they transferred information for completing a task on other devices "by hand", i.e., reading a text string on a display and typing it on another computer. A non-trivial number of people transferred data through shared files, FTP, or emails. Surprisingly, a more recent study in 2008 [13] showed that people were still using these old-fashioned mechanisms plus emerging cloud services (e.g., Google Docs) to transfer information across devices. Although cloud services and ubiquitous access to the Internet seem to be an antidote, the study found people were still frustrated as they have to manually reconstruct their work state, e.g., opening and locating the part of a PDF article that was viewed on the previous computer to continue reading. Furthermore, moving between heterogeneous devices (e.g., a PC and a mobile phone) amplifies the task resumption overhead due to various contextual and resource constraints [3, 2, 24].

Prior work made substantial progress in providing more integrated user experience for task migration across devices (e.g., [16, 30, 33, 37]). However, existing solutions are insufficient in two ways. First, some prior work primarily focused on infrastructure for transferring data across devices, not user interaction. Compared to moving data or application windows around on a single computer by drag-and-drop, there is no similarly easy method for cross-device migration. Secondly, existing tools focusing on user interaction are mostly document-centric with little support for recovering a work state [30, 3, 2]. Manually recovering a work state requires users to deal with many details that can distract them from the task that they want to resume.

To address these issues, we present Deep Shot, a framework that supports task migration by allowing users to transfer not only documents but also application states across devices using a mobile phone camera. Deep Shot provides two novel camera-based interaction techniques, *deep shooting* and *deep posting*. These two techniques allow seamless and intuitive migration of user tasks from one device to another by one uniform operation: taking pictures.

Deep shooting allows a user to capture and to persist the deep information, i.e., the information behind the raw pixels, such as application states, with a camera-like mobile phone application in a single click (see Figure 1-2). The captured work state can be resumed immediately on the mobile phone, opened later, or migrated to another device with deep posting, which pushes deep information to a device with a camera as well.

To support deep shooting and deep posting, we created a framework, Deep Shot, for application developers to easily incorporate these techniques into their applications. It includes two key ideas. First, Deep Shot uses robust computer vision algorithms to identify what portion of the screen the user is looking at through the camera. We conducted two experiments to show the feasibility of this technology. Second, Deep Shot requires the applications to encode the deep information as Uniform Resource Identifiers (URIs) to respond requests from deep shooting or posting so that a task can be resumed even using different applications, such as viewing a Microsoft Outlook contact's information with a native Android application.

In the rest of this chapter, we first clarify our motivation using a running example in which a user searches for a restaurant and discuss how Deep Shot supports this task by allowing a user to easily migrate the task across devices. Next, we discuss the design of our framework, and implementation details. We also show how developers can leverage our framework to enable deep shooting and posting in their applications. We then discuss the range of scenarios that Deep Shot can address. Finally, we describe an evaluation of our techniques and framework, and conclude with related and future work.

5.1 Motivation

Here we discuss why it is important to address task migration across devices. Let us assume a user, Bob, is searching for a restaurant for dinner on Yelp at home. Bob has read several reviews of a restaurant on his desktop computer. He decides to try one restaurant and clicks on the map on the review page to read the driving directions. Everything is going smoothly until he needs to leave home and move the directions to his mobile phone for navigation in his car. How can Bob open the same region of the map on his phone?

Bob could manually type the restaurant's address or name and search on the phone. Or he could click "Link" on Google Maps to get a bookmarkable URL of the current region, and email that URL to himself so that he can look for the email and open the URL in it on his phone later. These approaches generally require the user to perform two steps: 1) *inspecting* the internal state of the application, e.g., the URL, and 2) *copying* it by hand or via a temporary medium, e.g., a file or an email, from one device to another.

The inspecting step varies widely depending on the applications. In a web page or web application, the Uniform Resource Locator (URL) on the address bar often represents the application state that a user intends to transfer. However, in many web applications using Ajax, the URL no longer represents the current state of the application. A user is often required to perform extra steps to retrieve the real "bookmarkable" URL, such as what Bob would do in Google Maps. However, many Ajax and desktop applications do not have a URL that represents what the user is viewing and working on. Tools have been developed to overcome this problem by recording the commands needed to return a page [20]. However, a desktop application's state is generally inaccessible by end users.

The copying step requires a user to either manually re-enter the information on another device, e.g., when transferring a small piece of information such as a short URL or the name of a landmark, or understand and deal with low-level operations such as how to save information in files and use file transferring software.

Anecdotally, people sometimes take a picture of a particular region of interest (ROI) on the monitor using a camera, which is generally available on modern mobile phones. This method utilizes the camera as a physical tool to directly inspect and copy the information at the same time and saves the user's time from retyping the information on another device. In Bob's scenario, he could capture the portion of the map he needs in one simple step, i.e., taking a picture. This method is simple, independent of the application the user is using, and avoids many of the hassles of manual inspection and copying. However, it is limited in that information being transferred is encoded in raw pixels and will not allow a user to perform further interaction, e.g., panning or zooming a map.

5.2 Deep Shooting and Posting

Inspired by the picture-shooting metaphor above, we designed and implemented deep shooting and posting, two novel techniques that are as simple to perform as taking a picture, but copy *deep information* behind the raw pixels of the captured region, that is, the application state.

With deep shooting (see Figure 5-1), Bob can copy a specific region of the map displayed on his computer's screen to his mobile phone by simply taking a picture of it with the phone's camera. The same region is then shown on the phone automatically. More importantly, the captured map remains interactive on the mobile phone. In other words, Bob can pan the map to see the area that is not originally captured by the camera, or zoom in to see more details of the streets.

Based on the picture captured with deep shooting, our system automatically identifies the captured area on the screen and the front-most application containing that area. Our system then pulls information from the application and sends it to the mobile phone that took the picture. The information is encoded as a URI, which has been accepted as a stan-

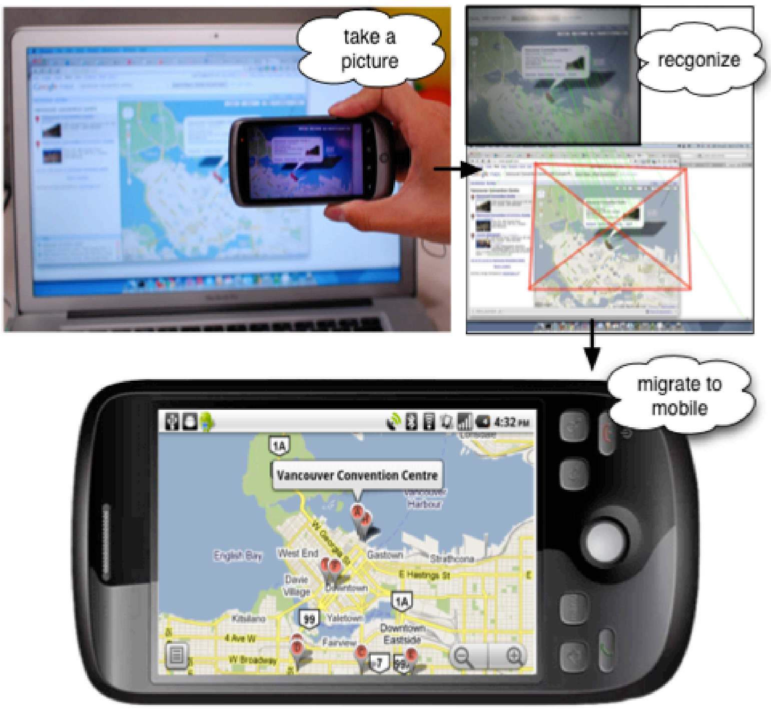


Figure 5-1: A user takes a picture of the screen of her computer and then sees the application with the current state on her phone. Our system recognizes the application that the user is looking through the camera, automatically migrates it onto the mobile phone, and recovers its state.

dard way to launch applications on contemporary mobile operating systems such as Apple iOS and Android. Therefore, the user can view or manipulate the extracted information on the mobile phone with native applications.

As a complement to deep shooting, deep posting allows a user to push information from a mobile phone to another device. Let us assume Bob has opened the restaurant review page on his mobile phone to write a review, but soon decides he would rather continue this task on his desktop computer, where it is easier to type. To do so, Bob aims the mobile phone camera at the computer screen with the review page still shown on the phone. Once deep posting is activated (e.g., via a hot-button on the phone), the review page becomes semi-transparent so that the user can see through it and know which part of the screen he is targeting at. Based on the screen region as seen through the camera, once Bob confirms, deep posting identifies the intended computer screen and automatically opens the same review page on it.

Deep posting employs the same mechanism as deep shooting in identifying the target computer screen and the specific region on the screen that the user sees through the camera. However, unlike deep shooting, deep posting does not need to identify which application the user is looking at, since the application for handling the information being posted may not be running.

The deep shooting application running on the mobile phone maintains the history of deep shots that a user has taken. Similar to browsing photos in a photo gallery application, a user can browse all of his deep shots (see Figure 5-2). Each shot in this gallery shows the title and the thumbnail of the captured application. With the gallery, a user can directly launch a desired application with its captured state on the phone. The gallery provides a simple interface for users to manage their tasks and switch between them.

Currently, the Deep Shot framework is designed for migrating tasks across personal devices. Thus, before using deep shooting or posting, a user needs to log into a remote server with the user's credential on each personal device, and the credentials can be stored in the devices thereafter. Therefore, this authentication step only needs to be performed once for each device. We will discuss the possibilities of eliminating the authentication process in the Future Work section.

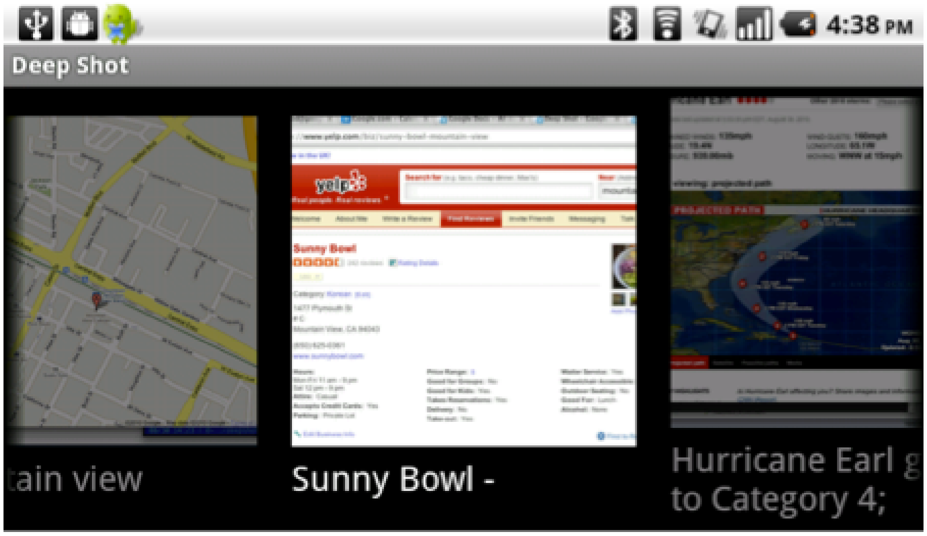


Figure 5-2: The Deep Shot gallery allows a user to quickly launch an application with a previously captured work state. A user can flip left or right on the touch screen to browse the gallery.

5.3 The Deep Shot Framework

To support deep shooting and posting, we designed the underlying Deep Shot framework with two goals in mind. First, from the user's perspective, deep shooting and posting should be as easy to use as taking a picture with an ordinary camera. Therefore, the user should not have to do any network configuration beforehand nor pair any devices to use Deep Shot. Second, from the developer's perspective, the Deep Shot framework should be easy to integrate with an application. Developers should not need to worry about the communication between devices nor understand how to detect what portion of screen the user is looking at through the camera.

To achieve these goals, we have to carefully choose the technologies for the link layer and the network layer. Many options exist for the link-layer technologies, such as IrDA, USB, FireWire, Ethernet, Bluetooth and WiFi. We chose WiFi/Ethernet for their ubiquity on almost all devices and then we can utilize the standard TCP/IP stacks. For the network layer, device discovery and association are still challenging obstacles today. Since we want to focus on migration across personal devices, we decided to base our framework on an instant messaging (IM) architecture, which was previously used in cross-device infrastructures such as PIE [33]. Thus, we can build on top of standard TCP/IP and avoid the problems of dynamic IP addresses, private IP addresses behind Network Address Translation (NAT) gateways, and firewalls that block connections from the outside. However, this architecture requires an authentication step before using our system. Fortunately, authentication only needs to be performed once for each device and does not add any cost for using Deep Shot thereafter.

We chose Extensible Messaging and Presence Protocol (XMPP), also known as Jabber, for our IM protocol. One reason is that XMPP supports logging in with the same user account from multiple different devices. A user account with a device has a unique identifier of the form "user@server/device." This allows users to set up all of their devices with the same user name. Since XMPP can list all of a user's presences across devices, users do not have to manually add their devices into their contact list. Also, the size of a XMPP message is not limited, which means we can send relatively large data, e.g., a JPEG photo, through a typical message packet without hacking the protocol.

5.3.1 System Components

Deep Shot's architecture is shown in Figure 5-3. The pink components are required for deep posting, whereas the yellow ones are required for deep shooting. There are five roles in our system: a *shooter*, a *poster*, a *dispatcher*, *launchers* and *applications (apps)*. The shooter and the poster only run on a *capturing device*, e.g., a mobile phone equipped with a camera. The dispatcher runs on a *target device*, which accepts a deep shooting or posting request from a capturing device. The launchers run on both sides of the system. On the capturing device, the launcher launches mobile applications to recover a work state captured by deep shooting, whereas on the target device it launches desktop applications to present a work state that is posted by deep posting.

5.3.2 Protocol Design

Here we describe the protocols between each pair of system components. To simplify the design of our protocols, the messages exchanged among all components are structured and

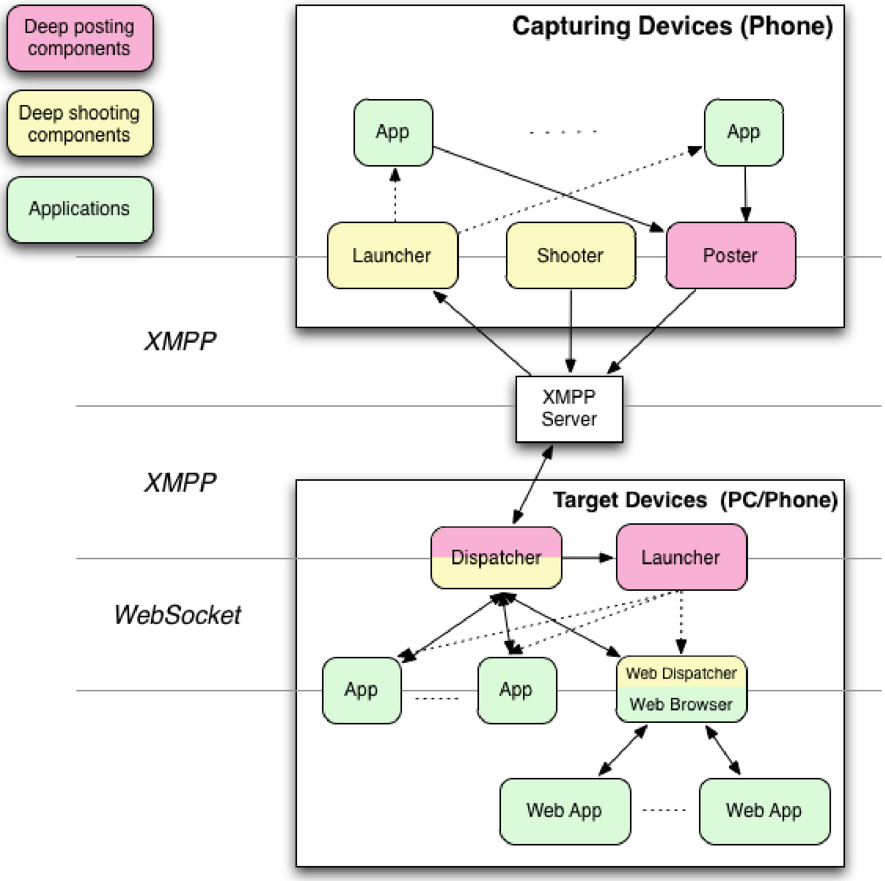


Figure 5-3: The system architecture of Deep Shot. Solid lines represent direct messages between components, whereas dotted lines represents the launching signal sent from the launcher.

encoded in the JavaScript Object Notation (JSON) key-value pairs. Besides, all binary data, e.g. images, are encoded in Base64 so we can include them in standard XMPP messages.

Deep Shooting: Shooter-Dispatcher Protocol

Once a user uses the shooter to take a picture of the region of interest on a computer monitor, an XMPP message with the picture and a subject *deepshot.req* indicating a deep shooting request is broadcast to all available devices.

When the dispatchers running on the target devices receive the request message, they immediately take a screenshot of the entire screen of their devices. Each dispatcher then matches the picture it receives against the screenshot. The matching algorithms (described in the next section) locate the region that the user was looking at through the camera. Then the dispatcher sends a new message with the x-y coordinates of the corners of the region and the central point of the region to the front-most application overlapping the center point, through a WebSocket connection.

After the application has handled the message and returned a response, the dispatcher inserts the application name, and the thumbnail of the matched region on the screenshot. Both are useful for browsing the deep shooting history on the capturing device. Finally, the dispatcher sends the response to the shooter via the XMPP server. If the picture matches on two different dispatchers, both send the response back and the client would pick the first response from them.

Deep Shooting: Application-Dispatcher Protocol

The dispatcher is designed as a daemon that always runs in the background on all personal devices. The dispatcher has the user's credentials, so it is always connected to the XMPP server. Therefore, any device can obtain the availability of any other device from the XMPP server.

The dispatcher communicates with each application using a dedicated WebSocket connection. WebSocket is a new protocol that supports full-duplex and bi-directional communication over a TCP socket. We choose WebSocket for two reasons. First, it is being standardized by the IETF and W3C, and modern browsers already support WebSocket.

Thus, we can easily implement a browser extension as a second-level dispatcher for web applications. Second, since the traditional TCP socket is the most pervasive inter-process communication (IPC) mechanism, and WebSocket is a simple extension of TCP sockets, traditional desktop applications can support it easily.

Each time an application that supports Deep Shot is launched, it registers itself with the dispatcher through a WebSocket connection on a TCP port. A registration process starts after the standard WebSocket handshaking. The application sends out a registration message with its name. If the dispatcher accepts the registration, it returns an OK message, or else it returns a decline message indicating the reason and closes the connection. To support deep posting, an application sends the command "accept URI_SCHEME", which indicates what types of URI schemes it accepts. For example, an email client can register the "mailto:" scheme, and a web browser can register the "http:" and "https:" schemes. Once the registration is completed, this WebSocket connection should be kept persistent until the application is closed so the dispatcher can proactively notify the application when a request is coming.

Once an application has dealt with the dispatcher's request, it replies with a message consisting of at least a URI that encodes the state of the application or the information to expose. If needed, the application can attach offline resources or files in the response message. Each attached file is stored in a JSON structure with the file name and the content of the file.

Deep Shooting: Dispatcher-Launcher Protocol

After the dispatcher receives a reply message from the application, it routes that message with a subject "*deepshot.resp*" back to the capturing device that sent out the request.

On the capturing device, a launcher waits for the "*deepshot.resp*" messages. Once a response message arrives, the launcher decodes the message and writes all attachments to the storage on the device. Finally, it opens an appropriate application that handles the URI replied from the target device to recover the work state and resume the task flow.

Deep Posting Protocol

The deep posting protocol is based on the same foundation we used in deep shooting, including JSON structures and XMPP communication. The key role in our system for deep posting is the *poster* that runs on a capturing device. The poster accepts requests from the applications that support our Deep Shot framework. The posting requests should consist of at least a URI representing the internal state of the application.

Once the poster receives a posting request from an application, it opens the camera and overlaps the screenshot of the application on the viewfinder so that a user can see the target device and the information to post at the same time. After the user has confirmed the target device through the viewfinder, the poster creates a "*deeppost.req*" message with the picture taken by the camera and the request from the application. Finally, this message is sent to all available devices, in the same way as deep shooting.

After the dispatchers running on the user's other devices receive the "*deeppost.req*" message, each of them runs the same vision algorithm used for deep shooting to match the picture taken by the user against its screenshot. If a dispatcher finds a match, it routes the request to the launcher.

As we mentioned before, applications register the types of URI schemes they support. The deep posting launcher requires this information to launch an appropriate application for the given URI in the request. Each application may register multiple URI schemes. If a URI scheme can be accepted by multiple applications, the launcher either opens a dialog so the user can choose an application or just launches a previously specified default application.

5.3.3 Screen Matching Algorithms

Once a device receives a Deep Shot request, it takes a screenshot of the entire monitor. It then extracts visual features from the screenshot and the picture taken by the camera, using a computer vision algorithm, Speeded-Up Robust Features (SURF) [4]. SURF is robust against scaling and rotation, and faster and more robust than Scale-Invariant Feature Transform (SIFT) [28], another popular feature extraction algorithm.

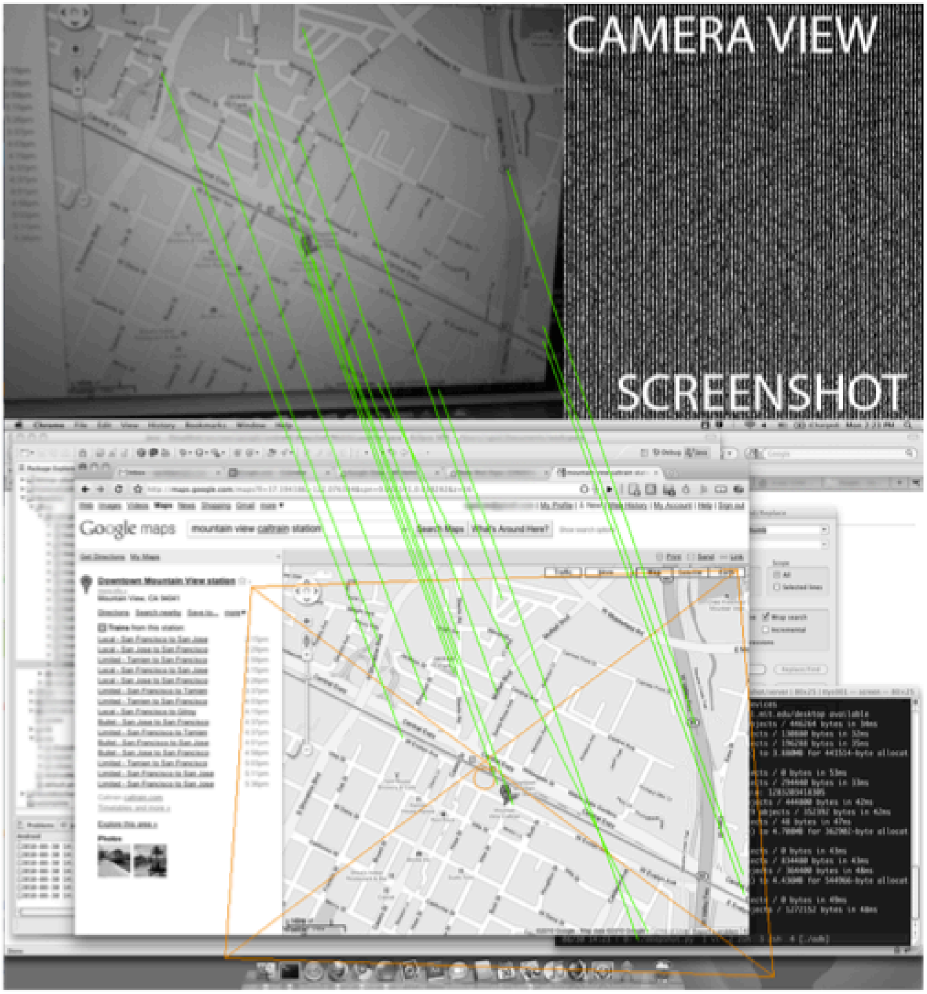

CAMERA VIEW
SCREENSHOT
Google maps
mountain view caltrain station
Downtown Mountain View station

Figure 5-4: The screen matching algorithms match the picture (at the top) against the screenshot (at the bottom) and find a projective plane (the orange convex) on it.

We use SURF to detect the key points, which are represented by feature vectors, on the screenshot and on the picture respectively (see Figure **??**). We then compute the cosine similarity between each pair of key points and find the nearest neighbor for each point. Finally, with the paired key points, a homography (the perspective transformation between two planes) can be calculated to find the projective plane on the screen image. Thus, the region of the screen that the user sees through the camera can be located.

5.3.4 Content and State Encoding

A migration process of an application consists of transferring not only its content but also its states. With our framework, developers can store arbitrary offline content, e.g., files, as an attachment in a Deep Shot request and encode the application states into a URI. A URI is the key element to resuming a work state in Deep Shot. A URI can be application independent. For instance, "content://contacts/15" opens a contact manager to show the person with the id 15; "geo:*latitude,longitude*" shows the given location in a map application; and "document://chi2011.pdf/3" represents the third page of the file "chi2011.pdf". Furthermore, developers can append the zoom level, the scrolling position, and all necessary information of this document to the URI as needed. We do not limit the length of a URI so arbitrary states of an application can be encoded.

Recently, some application frameworks such as Three20 (http://three20.info) have started to support URL-based navigation in traditional applications. Mobile operating systems such as Android and iOS also support launching applications with standard URIs (e.g., http:, tel: and geo:). Deep Shot allows applications to create their own URIs, although it is advisable to be compatible with public standards.

5.3.5 Bootstrapping with a Default Responder

To handle the work state of various applications, the Deep Shot framework, needs to be integrated into those applications by their developers. To deploy such a framework, we need to address how to bootstrap its usage when application developers have not yet adopted the framework. Therefore, we implemented a default responder in the dispatcher to handle the case in which the target application does not support Deep Shot.

If the application that the user is taking a photo of is not registered with the dispatcher, the default responder replies the screenshot of the entire screen to the capturing device as well as the coordinates of the matched region. Therefore, users can acquire a clear version of the screen, i.e., without any noise and distortion caused by the physical camera. They can also zoom in to see more detail and pan to other parts of the screen that were not in the original picture. In addition, as the dispatcher takes the screenshot, it also detects clickable

URLs and information of interest such as phone numbers or addresses, using the operating system's accessibility API. These metadata are also transferred along with the screenshot, so the user can tap on a URL or a phone number on the screenshot to launch a browser or dial the number directly.

5.3.6 Supporting Web and Desktop Applications

Deep Shot is a general framework that supports traditional desktop applications as well as web applications. We discuss how Deep Shot supports these two kinds of applications in this section.

Most modern web applications are written in JavaScript and run inside a web browser, while their data are stored on remote servers. To further bootstrap the Deep Shot framework and support this kind of application, we created a *web dispatcher*, implemented as a Google Chrome browser extension, which has three important features.

First, the web dispatcher acts as a second-level dispatcher. It routes messages from the first-level dispatcher to the appropriate web page and sends reply messages back (see Figure 5-3).

Second, the web dispatcher is a default responder for all web applications that do not support Deep Shot. If the web dispatcher gets a request asking for data from a site that does not register itself with Deep Shot (discussed in a later section), it will only return the URL to that site as a default response. The URL on the address bar often maps to the state of the current web application. However, some Ajax applications do not have this property or hides their real URL on purpose. Fortunately, the last feature of our dispatcher addresses this problem.

Last, the web dispatcher can inject a script into a web application that allows Deep Shot to extract the application's state, without the application knowing about Deep Shot. This is possible because, as a browser extension, the web dispatcher is capable of injecting any content into any web page from the browser.

In addition to web applications, desktop applications could be more difficult to migrate since their developers need to make additional effort to encode the application states into a URI. Fortunately, most mobile versions of a desktop application are simplified and only provide the key features on the mobile devices. This means the developers do not need to encode the complete state of their applications, but can focus on a small set of key states. For example, the key states of a word processor may only consist of the cursor position, the zoom level, and the scrolling position of the document. The other states, such as the view mode and the toolbar's style, could be unimportant because the mobile word processor does not have these adjustable features.

5.4 Implementation

We implemented Deep Shot to support both deep shooting and posting. On the mobile side, we chose the Android platform and implemented the system in Java on a Google Nexus One phone. On the other side, we implemented the dispatcher and the launcher in Python on a laptop computer. We also set up a XMPP server using Jabber on a Linux machine. Besides disabling the message size limit in Jabber's default configuration, we did not modify Jabber.

5.5 Developing Deep Shot Extensions

To minimize the effort for developers to incorporate Deep Shot into their applications, we created a Java library that implements the dispatcher-application protocol and hides the WebSocket connection inside the library.

The library has a DeepShot class that has one public method, `addListener` (defined as follows), for applications to register themselves to listen to Deep Shot requests.

```
void addListener(Listener listener, String app_name, String[] accepted_uris)
```

The `Listener` interface has only one method, `DeepShot.Response onShot(DeepShot.Request req)`, where the `Response` contains a URI and optional file attachments, and the `Request` contains the four corner points and the center point of the ROI. Deep posting also has a similar API, `void post(DeepPost.Request` req) in a class DeepPost, where DeepPost.Request contains a URI and optional file attachments.

For web developers, we also provides a JavaScript function, DeepShot.addListener(listener), from a browser extension, so web developers can simply hook their web applications into Deep Shot. For example, Google Maps does not show the URL of the current region of the map in the address bar. To extract the real URL of the current map, we inject the following script:

```
if(window.DeepShot){
  DeepShot.addListener(function(request){
   return {"uri": document.getElementById("link").href};
  });
}
```

With this script, even if Google Maps does not support Deep Shot, users can still use deep shooting to open any computer map on their phone.

5.6 Scenarios

In this section, we illustrate four typical scenarios that can be accomplished by deep shooting and posting.

Scenario 1: Taking information to go (PC to mobile phone)

This is the classic scenario that motivated us to develop deep shooting. People usually work on desktop computers or laptops at work or home. Before moving to another place, they may look up the information related to that place on their computers. However, as the information may be hard to remember, they often write down the information on a piece of paper or look up the same information again on their mobile phones. In this scenario, people can take the information with them using deep shooting. For example, people could carry a part of a map or the address of the next meeting place so that they do not need to look it up again. People could even capture a YouTube video being played and later resume watching the video from where they left off on a mobile phone.

Scenario 2: Viewing or saving mobile phone content on PCs (mobile phone to PC)

People generate various kinds of lightweight information on mobile phones, such as photos, contacts, or unfinished readings. For lightweight tasks, such as transferring a photo in a phone to a PC so that more people can see it, using existing software tools for syncing up mobile phones with PCs is cumbersome (e.g., a user might need to plug in the cable and find the right folder). With deep posting, users can simply aim their camera at the target computer monitor with the photo still shown on the mobile phone. The photo will be automatically transferred and opened on the target monitor. Deep posting also allows an application to post information at a specific position and size, as seen through the camera, on the target screen, e.g., a Post It application, which cannot be achieved by Bluetooth-based sync tools.

Scenario 3: Using mobile phones as a bridge between PCs (PC to PC via a mobile phone)

USB flash drives are widely used to share files among computers. People are used to saving the information they want to share as files onto a USB drive, and then taking the drive to another computer. In this kind of scenario, deep shooting can be used to extract information from an application (e.g., running on an office PC) and automatically transfer it to a mobile device. The user can then take this mobile device to a home PC and post the extracted information or work states onto it with deep posting.

Scenario 4: Sharing content between mobile phones (mobile phone to mobile phone)

Although it is still rare to share information between multiple personal mobile devices, it is common to share information between mobile phones owned by different people. Researchers have developed techniques to address this need. For example, bumping is a synchronous gesture to connect two mobile devices [19]. Although the current Deep Shot framework does not support communication between multiple users' devices, deep shooting and posting can be used to locate the devices as well as the region of information to share across multiple users. For example, a user could take a picture of a contact displayed on another person's mobile phone with deep shooting, and then the full contact information would be automatically transferred to our phone. This scenario potentially requires a different authentication mechanism though.

5.7 Usability Analysis and Technical Evaluation

We analyze and evaluate this work from three perspectives. From a user's perspective, we analyze the interaction model and the usability of deep shooting and posting. From a developer's perspective, we analyze the usability and the utility of the API that we provide for developers. Lastly, from a technical perspective, we evaluate the performance of our framework and the feasibility of using a camera to locate a region on a monitor.

5.7.1 Interaction Model and Usability Analysis

Traditional GUI applications on PCs provides an action such as "send this to ..." in their menus to let users send local files to remote devices. However, we argue this model is less intuitive than the deep shooting and posting. For the same task of migrating applications across devices, in the traditional model, a user would need to select the source application, the data of interest, and the target device from a list of names or identifiers in multiple steps with a GUI, which can distract the user from the task. In contrast, deep shooting and deep posting adopts an old technique - taking pictures using a camera - to simultaneously identify the source device, the data to transfer, and the target device, all in one action of taking pictures of computer screens, which is just as easy as doing so of the real world. This is consistent with the informal feedback we collected from users.

Since there is no extra step beyond taking pictures, the learnability and the memorability of our techniques are as good as using ordinary cameras on mobile phones. The efficiency of our techniques is related to two factors. One is the steps performed by the user, and the other is the performance of our system in terms of speed and accuracy. To do a deep shooting or a deep posting, a user needs to perform three steps: launching our application on a phone, locating the target window on a device through the viewfinder, and pressing the shutter. These steps are exactly the same as taking a picture using a camera application on a phone. Therefore, our techniques are as fast as taking a picture from a user's perspective. The other factor, the speed and accuracy of our system, will be discussed later from the technical perspective. Finally, because the steps a user needs to perform are minimized, the type of error that may occur is taking a wrong region on the screen. However, the user can simply discard an incorrect capture and redo the procedure. In addition to user errors, our system may have errors while matching pictures against screenshots. We will examine this kind of error with a controlled experiment in the following sections.

5.7.2 Technical Evaluation

Finally, we evaluate our system from a technical perspective. We set up two experiments to explore whether using a camera to locate a region on a monitor is feasible in terms of speed and accuracy. The first experiment was to test the speed of our system, and the second one was to test the accuracy of our image-matching algorithm.

Experiment 1: Speed Performance

We used a laptop, a 15-inch MacBook Pro with a high-resolution 1680Œ1050 monitor as the target device, and a Nexus One running Android 2.2 as the capturing device that takes 512x384 pictures. The capturing device was held by the experimenter at a distance of 20 to 40 cm and a pitch angle of $\pm 20^\circ$ so that about $\frac{1}{3}$ of the screen could be seen through the viewfinder.

We tested four target applications: photos (from Google Street View), short textual information (from Yelp.com), long textual article with a few images (from CNN.com), and maps (from Google Maps). For each application three photos were taken using deep shooting under the setting described above.

The average time of the whole procedure across 12 trials (3 pictures for 4 applications) was 7.7 seconds (SD 0.3 seconds). By examining the average time of each step, we found

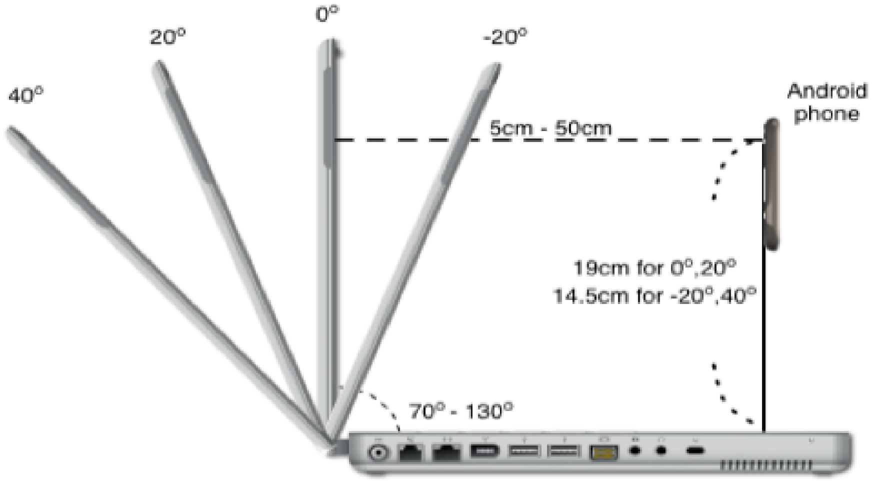


Figure 5-5: The setup of the reliability experiment.

the network transmission occupied about 50% of the total time, while the rest of processing time was spent on the target device (34%) and the capturing device (16%). The transmission caused a significant portion of the latency because our current implementation attaches raw images captured by the camera in the messages and these messages were routed via an external server. As a result, we can significantly reduce the latency of our system by improving the transmission efficiency, e.g., using only visual features instead of the entire image and not using a third-party server. We will discuss the possibilities in the Future Work section.

Experiment 2: Reliability

In this experiment, we wanted to test the accuracy of our image-matching algorithm under typical conditions for taking a picture of a screen as well as extreme conditions that are not so common. Our experimental setup is shown in Figure 5-5. We used a 15-inch MacBook Pro laptop so that we could easily adjust and measure the pitch angle of the screen. We tested four pitch angles for the screen with respect to the phone: $-20°$, $0°$, $20°$, and $40°$. The laptop shows a full-screen browser (Google Chrome) with a web page of the most popular local restaurant on Yelp, which is a typical webpage consisting of text and images. An Android phone, Google Nexus One, was tied to an L-square ruler that is perpendicular

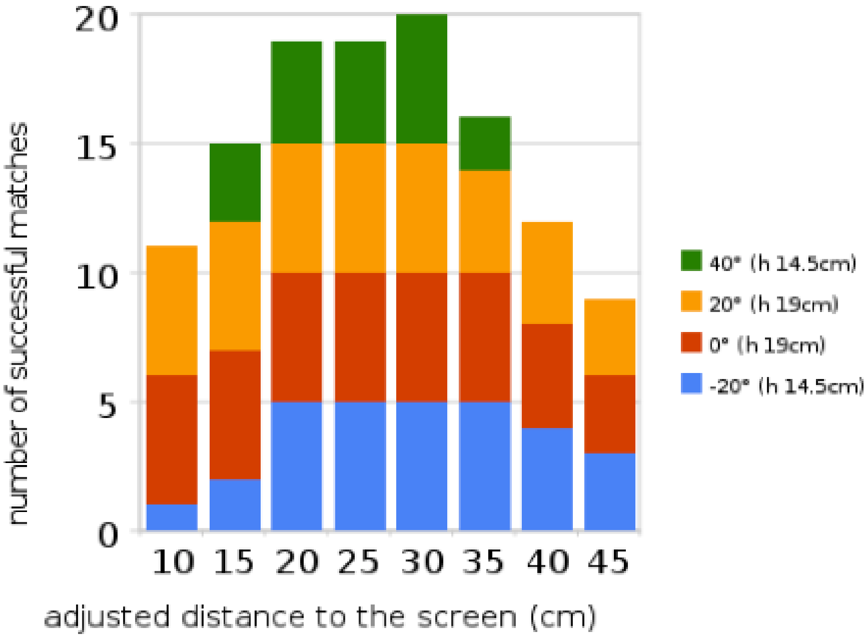


Figure 5-6: The results of the reliability experiment. The total number of trials for each setting is 20.

to the floor. The height of the camera, which was measured from the surface of the laptop keyboard to the center of the camera lens, was fixed at 19 cm while the pitch angle was $0°$ or $20°$, and 14.5 cm while the pitch angle was $-20°$ or $40°$. These height settings allowed the camera to focus around the same target on the screen, namely the name of the restaurant. We set the phone in front of the screen with a distance of 5 to 50 cm, as measured from the screen shaft to the camera lens. Finally, for each pitch angle, we took five pictures for every 5 cm between 5 cm and 50 cm, which resulted in a total of 200 pictures. This experiment was conducted in an office with ceiling fluorescent lights.

We used the algorithm mentioned before to match each picture against the screen displayed on the laptop. If the center of the matched region overlapped the expected region on the screen, it was considered as a successful match.

The results of this experiment are summarized in Figure 5-6. The chart shows the number of successful matches for each adjusted distance to the screen, instead of the distance measured to the screen shaft. Because the screen was tilted, we adjust the distance to the shaft by adding h tan θ, where h is the height of the phone and θ is the pitch angle. With

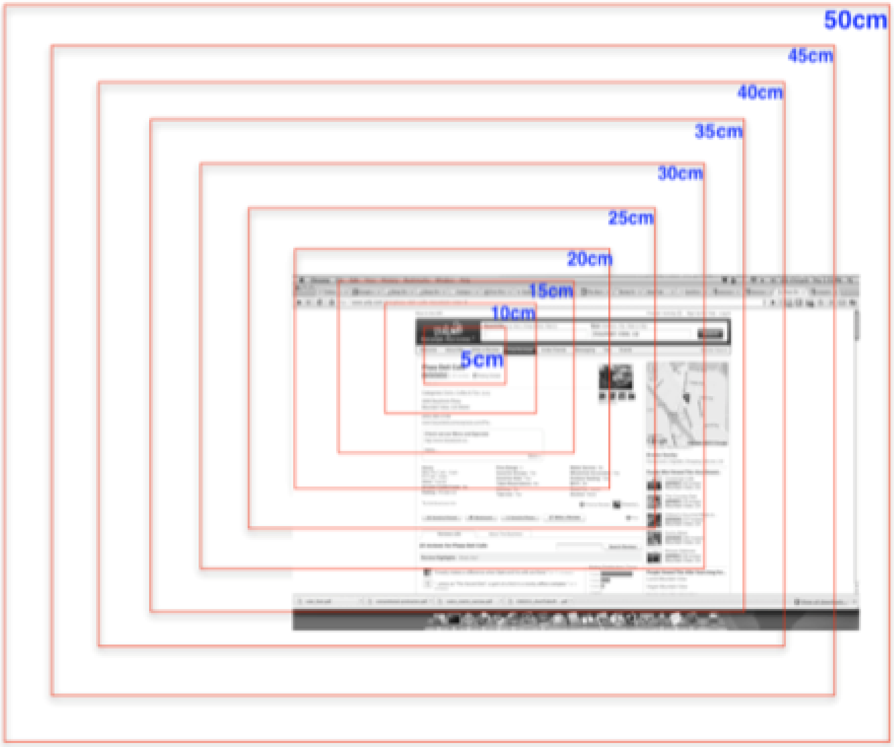


Figure 5-7: The regions the camera sees with a distance 5 to 50 cm away from the screen while the monitor is parallel to the phone.

this adjustment, we only show the results between 15 cm and 40 cm where all the settings have valid measurements.

The experiment showed that the matching algorithm was highly robust with a 97% success rate, when the camera was parallel to the monitor and the distance between them ranged between 10 and 40 cm. This range is sufficient to cover everything from a small region, such as a restaurant's name, to the entire screen (see Figure 5-7). Even when the camera was tilted, taking pictures in the range of 20 to 30 cm was still robust (96.7% success). The accuracy significantly decreased when the camera is too close to (< 10 cm) or too far (> 40 cm) from the screen, but these conditions are uncommon as users can seek the appropriate size of the target through the camera. The results of this experiment showed that using a camera with our algorithm was robust enough to locate a region on a monitor.

5.8 Conclusion and Future Work

We conclude by discussing the limitation of Deep Shot and possible extensions for future work.

Multiple users: Our current system finds possible target devices from a list of the user's online devices. It is easy to add other users' devices into the user's "friend list," so that they can be notified when a capture event happens. However, this would add extra effort of managing the device list. A possible solution is to replace the XMPP layer with a local service discovery protocol, such as Apple Bonjour, and broadcast the request to local devices.

Transmitting visual features instead of pictures: In the current implementation, we send pictures directly in a request, which raise privacy concerns since the devices that receive the request can "see" the pictures, especially for a multiple-user environment. Therefore, a possible solution is to extract the visual features directly on the capturing device and only send the feature vectors in a request. This could dramatically speed up the performance and also prevent malicious request sniffers. In addition, this could enable real-time matching feedback on the target screen, so users can be confident that the matching is successful and also know which region of the screen will be captured.

Limitation on feature matching: Feature matching may not work in some scenarios. For example, nothing can be extracted and matched if a user intends to capture a blank region. However, we can assume that no valuable information exist in this area and simply show the photo she took back to her. A more common problem is unfocused photos, although this could be solved with the real-time matching feedback we mentioned above.

This chapter presented two novel interaction techniques, deep shooting and deep posting, to migrate a task across devices and a robust and extensible framework to support them called Deep Shot. We demonstrated that Deep Shot is reliable and feasible to support a range of everyday tasks migrating across devices using one simple gesture.

Chapter 6

PAX

Pixels are the most common characteristic and the ultimate elements produced by every application with a graphical user interface (GUI). However, pixel-level interpretation for GUI automation, testing, and customization have room for improvement in terms of speed and accuracy. For example, Sikuli Script (described in Chapter **??** is not very fast, because it searches the screenshots of GUI elements across the whole screen and does not know how to narrow down the search space. Furthermore, it is hard to detect and extract the text content from pixel data. Current Optical Character Recognition (OCR) algorithms are designed for scanned documents, which are high-resolution with white background and simple column-based layouts, but not for on-screen text, which is low-resolution with colored background and could be randomly placed on the screen. Using current OCR algorithms on screen text would generate poor results [45, 43]. (See Figure 6-4 for an example.)

In order to maintain platform independence, current pixel-based systems have intentionally neglected the other information that can be obtained from window managers or accessibility APIs. Unlike pixels, these extra sources of information are not necessarily available. For example, accessibility APIs are the standard hooks for exposing the internal structured metadata of a GUI to third-party assistive programs, such as screen readers, but to support such APIs requires engineering effort from individual software developers. As a result, accessibility hooks may be omitted or added later as the software matures. Fortunately, even not all applications, some popular commercial applications and built-in software on modern operating systems are accessibility-enabled. Hurst et al. reported that 74% of the widgets in eight popular applications were correctly identified by the accessibility API [21]. Therefore, why not leverage the accessibility metadata if the target applications provide them?

This chapter introduces PAX, a hybrid framework combining *Pixels and Accessibility APIs*. PAX enhances the capabilities of current pixel-based systems and enables new interactive applications on top of existing interfaces. The key insight is that accessibility and pixel interpretations complement each other. Thus, both of these sources of information should be used together if possible.

PAX combines pixels with other information sources provided by GUIs, including accessibility metadata and low-level rendering data from the window manager, and associates the pixels with their internal hierarchical and structured attributes. As a result, PAX not only knows what is visible to the user on the screen but also understands the content and structures behind the pixels. We use accessibility metadata as a convenient and accurate source of widgets' information. If the accessibility metadata is not available, PAX automatically switches to pixel-level interpretation and still returns useful data. Furthermore, we use pixel-level methods to optimize the accessibility metadata. For instance, when accessibility APIs are not fine-grained enough to return the position of each word in a paragraph of text, we use a pixel-based segmentation algorithm, along with the known text for the whole paragraph obtained from the accessibility API, to locate the words with high precision.

The potential impact of PAX lies in its ability to improve existing pixel-based systems and to enable implementation of novel interaction techniques on top of existing interfaces. We validate this claim with concrete examples: the enhancement of pixel-based GUI automation (i.e., Sikuli Script [49]) and the implementation of two novel applications: *Screen Search* and *Screen Copy*. Screen Search allows users to conduct text-based search across multiple applications over the entire desktop rather than being limited to a particular window. It is applicable to any GUI components with text on the screen (e.g. on a title bar or in a tooltip of a button), even if it is occluded by other windows. Screen Copy allows users to copy the text content of a GUI component as well as the component itself. Users can paste the copied text into a text editor or reuse the copied component in a GUI designer application. The tool can be applied even when the text is not selectable or when the source code of the GUI is not available.

We make the following contributions in this chapter:

- A hybrid framework that demonstrates how pixel analysis and accessibility metadata can be used together and complement each other.
- A text detection algorithm that finds text in screenshots, even with colorful backgrounds.
- A text segmentation algorithm that segments an image of a paragraph of text into individual word images, given known text from the accessibility metadata.
- Validation of the framework in two novel applications and one enhancement of an existing system.

6.1 Pixel Analysis Versus Accessibility API

In this section, we describe the advantages and disadvantages of pixel-based methods and how we can use accessibility APIs to enhance the capabilities and performance of those methods.

6.1.1 Pixel Analysis

Pixels are the most common output medium of current computing devices. Every GUI application is eventually rendered as pixels on a screen. Unlike the pixels perceived from the real world and generated by a digital camera, the pixels generated by a computer itself have no noise, no distortion, and no other source of interference. Thus, early systems were able to use naïve bitmap matching to find targets on a screen [34, 51]. Furthermore, Prefab has demonstrated that a UI model can be built from pixels in real-time so that researchers can build new interaction techniques on top of existing interfaces [14, 15].

In contrast to understanding the UI model behind pixels, Sikuli Script takes a different approach to automate existing interfaces. In order to let users use loosely-bounded screenshots of automation targets, Sikuli uses template matching to fuzzily find the screenshots on the whole screen.

While they hold promise, the effectiveness of pixel-based methods can be challenged by four factors:

- **Visibility constraints.** Invisible information, such as the items out of the current scrolling area or even the targets that are occluded by other windows, cannot be detected by pixel-based methods.

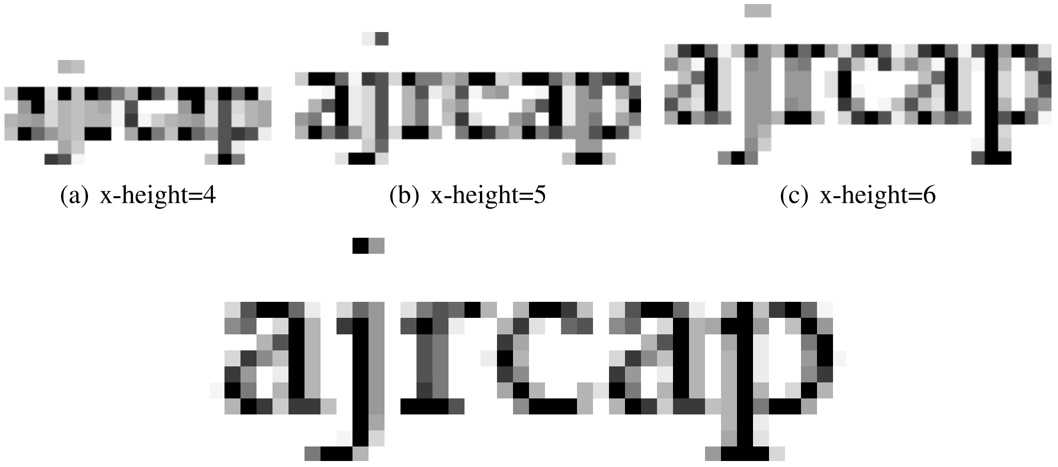
- **Visual variations.** The accuracy of pixel analysis depends heavily on the look of target interfaces. If the user makes dramatic changes to the color scheme or the application theme, neither Prefab's trained prototypes nor Sikuli Script's fuzzy template matching screenshots can deal with the visual variations that result from such changes.

- **Exhaustive screen search.** Pixel analysis is a potentially expensive operation, especially in high-resolution and multiple monitor environments with many millions of pixels. However, existing pixel-based methods such as Sikuli and Prefab often need to consider every pixel on the screen indiscriminately in order to locate certain targets, unless there is an external mechanism to direct their attention to specific regions on the screen.

- **Low-resolution text.** The text content of an interface is hard to extract purely from pixels. Existing OCR engines are designed for high-resolution (150 to 300 DPI) scanned documents with white background and simple column-based layouts, but not for low-resolution screens (72 or 96 DPI) with colorful backgrounds and arbitrary layout. (See Figure 6-1 for examples of low-resolution text.) Simply plugging an existing OCR engine into a pixel-based system does not immediately work.

6.1.2 Accessibility API

Accessibility APIs are the standard interfaces built in modern desktop operating systems for assistive applications, such as screen readers, to access the low-level information of a user



(a) x-height=4 (b) x-height=5 (c) x-height=6

(d) x-height=7

Figure 6-1: Low-resolution and antialiased text on the screen is very difficult to be recognized with off-the-shelf OCR engines.

interface. Accessibility metadata is hierarchical, structured, and precise. For example, on Mac OS X, for an "OK" button in a confirmation dialog, we can get its role (AXButton), role description for humans, title, help message (the tooltip), enabled or disabled state, parent component, parent window, position, size, etc.

Accessibility APIs provide a convenient way to access many low-level attributes of existing software. However, to support such an API, application developers have to put in extra engineering effort to correctly expose the internal data. As a result, not every application and GUI widget supports accessibility APIs. Hurst et al. reported that only 74% of the widgets in eight popular applications were correctly identified by the accessibility API [21].

We conducted our own investigation into the current accessibility APIs for Mac OS X and Microsoft Windows (Microsoft Active Accessibility) regarding their capabilities and application compliance. We identified five challenges:

- **Indifference to visibility.** Accessibility APIs does not know if a window or a GUI component is visible or not (see Figure 1-3(a)). The location and the size of a minimized window would be returned as its original place and size before minimizing. If items are out of a scrolling area, they still can be reached by the accessibility API, and there is no way to tell which of them are visible to the user. This can lead to excessive and incorrect information when the developer just wants information about those the visible objects.

- **Point-based object access.** Accessibility APIs support hit testing to gain access to an interface object shown on the screen. However, this ability is point-based and is limited to a single object. In many scenarios, such as in Deep Shot and Sikuli Script, the user could select an arbitrary region on the screen, which consists of multiple objects within that region. Therefore, we need a mechanism to allow accessing a group of objects in a given region.

- **Incomplete support.** Even applications that support accessibility APIs may not do so completely, as confirmed in the study of Hurst et al. [21]. An application may include new or complicated widgets that do not provide any accessibility metadata because they are not in the standard widget set.

- **Coarse granularity.** The granularity of accessibility metadata may not fulfill the developer's needs. For example, the text content of a document may be returned as a block of text, where a novel interface technique may need the location of each individual word.

- **Inconsistent text.** The text shown on an interface is not necessary consistent with the accessibility metadata, as it can be reformatted in an unknown way. For example, a date in accessibility metadata is "Friday, April 15, 2011 10:48:27 PM ET" but could be displayed as "Today, 10:48PM" on the screen.

Recognizing the respective strengths and weaknesses of pixels and accessibility APIs, we believe it would be ideal to combine them in a complementary manner, offering both generality from pixels and precision from accessibility metadata at the same time.

6.2 PAX: A Hybrid Framework

We propose PAX, a Pixel+Accessibility hybrid framework that associates the high-level visual representation of GUI widgets with their low-level structured and hierarchical infor-

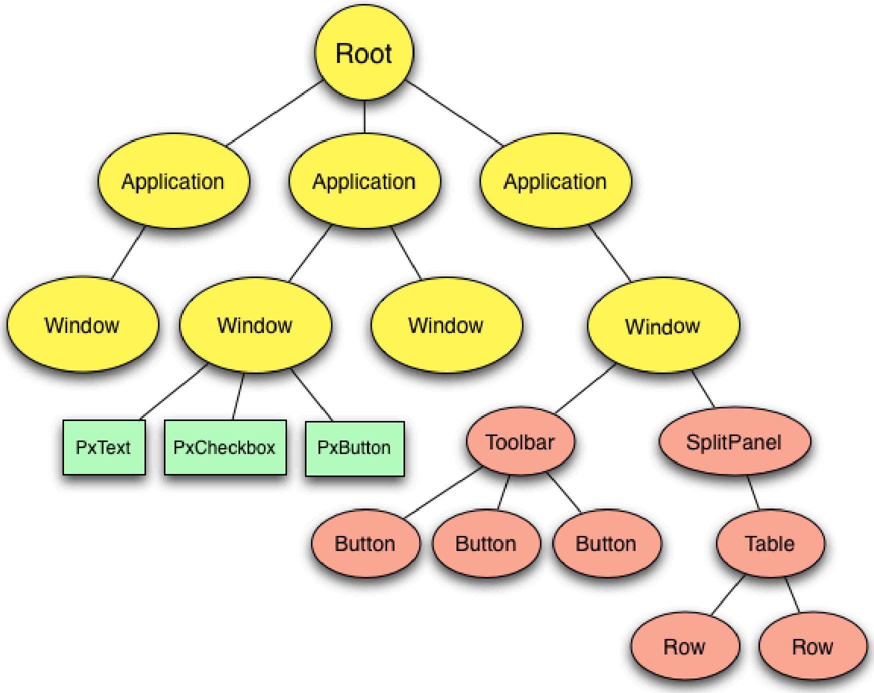
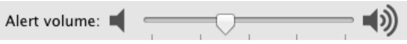


Figure 6-2: The tree of PAX UI elements. The yellow nodes, created using accessibility and window manager information. The red nodes are the elements exposed using accessibility APIs, while the green ones are reverse engineered from pixels.

mation. PAX has three sources of input: pixels, accessibility APIs, and window managers. PAX consolidates the information from these three sources into a new API that allows developers to easily access not only the pixels of the GUI widgets on the screen but also their internal information.

PAX associates the pixel representation of each GUI element on the screen with its underlying attributes, such as its role (which could be a button, a text field, etc.) and its text content or value. The underlying attributes are retrieved from the accessibility API if available. If not, PAX attempts to infer the role of the element from its pixel representation using template matching and uses pixel-based algorithms to detect and recognize the text (see Figure 6-2).

PAX can improve the effectiveness of existing systems that are based purely on accessibility APIs or on pixels. On the one hand, systems based on accessibility APIs can benefit from the knowledge of the GUI's apparent visual representation to resolve certain ambiguities. On the other hand, pixel-based systems can use PAX to improve speed and accuracy. For example, PAX enables identification of a particular UI element using an XPath. Sikuli Script can store the XPath to a target UI component when taking the screen shot of it along with the screen shot image (e.g. in the header of the PNG file) and later use that path to locate the component without running template matching on the whole screen, or to constrain the search in a smaller region. Furthermore, PAX enables Sikuli Script to accept simple commands, e.g. `find(` `).value()`, to easily retrieve the value of a slider without calculating the position of the thumb to infer it.

6.2.1 Designing PAX

There are three design goals for PAX:

1. The framework should enable existing pixel-based systems to easily access internal widget information given a region or a point on the screen.
2. The framework should simplify the difficulty and complexity in implementing novel interaction techniques on existing interfaces.
3. The framework should automatically give the most accurate results from available resources (either from accessibility metadata or pixel reverse engineering).

PAX maintains a tree of *UIElement* objects shown on the screen. The root of this tree is a virtual node, which does not represent any physical GUI elements. The root returns all running applications as its children and can be obtained by calling a global function `getUIElementRoot()`. Each application is also a UI element, which returns its opened windows. Each window recursively contains the same hierarchical structure of its title bar, tool bar, and all the other UI elements.

PAX distinguishes three different visibility levels for a UI element:

- **Visible.** This element can be fully seen on the screen, or partially seen because of parts of it are scrolled out.

- **Virtually visible.** This element is meant to be visible on the screen but is partially or entirely occluded by other windows in front of it because of limited screen space; if the screen was infinitely large and no windows needed to overlap, this element would be completely visible.

- **Invisible.** This element is not meant to be seen by users because it is scrolled out of view, in a minimized window, or hidden by design.

Therefore, each UI element has three different methods to get its children according to their visibility: *getVisibleChildren()*, *getVirtuallyVisibleChildren()*, *getChildren()*, where they return the visible children, virtually visible children, and all children, respectively. Because a UI element may be partially invisible, PAX also provides two methods, *getVisibleBounds()*, which returns the bounds of the visible part of a UI element, and *getBounds()*, which returns the original bounds.

Like accessibility APIs, PAX provides *getRole()*, *getText()*, and *getValue()*, for getting the role, the text, and the value of a UI element, respectively. A role represents the type of a component, e.g. a button or a list item. Text can be the label or the string value of a component, such as a text label or text field. A value is a number that is only meaningful for some components, e.g. a slider or a check box. These values are retrieved from accessibility APIs if they are available; otherwise pixel reverse engineering techniques are used. Further, PAX also provides *getVisibleText()*, which returns the text actually shown to the user.

In addition to the standard accessibility attributes, each UI element has a *getScreenshot()* method for getting the screen shot of the element even it is only virtually visible, and *getXPath()*, which returns an XPath to the element, such as */Application[name="Word"]/Window[1] /TabGroup[1]/Group[text="Paragraph"]/MenuButton[text="Bulleted List"].* The name attribute in an XPath is only valid for Applications nodes, whereas text and value can be used in the remaining nodes. Developers can save the path and locate the same element quickly with a global function *locateUIElement(xpath).*

To find particular elements, two methods can be used, by screen location or by content. PAX supports single-point hit testing with *getUIElementAtPoint(x, y)*, which returns the element at the given point, and *getUIElementsInRect(rectangle)*, which returns all the visible elements in the given rectangle on the screen. To find by content, each UI element has the three methods *findChildren(pattern)*, *findVisibleChildren(pattern)* and *findVirtuallyVisibleChildren(pattern)*, which return all, visible, and virtually visible children whose text content matches the given regular expression pattern.

Finally, to better support advanced interaction techniques, each UI element has a method *focus()*, which sets the keyboard focus to that element and also brings its parent window to the front at the same time. This is particularly useful when the developers need to perform further interaction on a UI element.

6.2.2 Bridging between Accessibility APIs and Pixels

One of this framework's goals is to automatically give the most accurate results from the available resources. Therefore, PAX constructs the UI element tree from all running applications and their corresponding accessibility handles. If an application has exposed all necessary accessibility hooks, its descendants in the PAX tree are simply copied from the accessibility tree and wrapped up with a *UIElement* interface. Sometimes a few widgets or even the entire application do not support accessibility APIs, and in this case, each of these widgets or windows looks like a black hole, with only a single node in the accessibility tree to record its boundaries.

When PAX walks down the accessibility tree and reaches a leaf node, it determines if there is a need to reverse engineer the pixel contents of the node with three simple rules: (1) if the node is a text component (e.g. a text label, a text field, or a text area), run our text segmentation algorithm to breaks the text into word component pieces; (2) if the node's role is not a container and not a text component (e.g. it is a check box, a radio button, etc.), do nothing; (3) otherwise run pixel reverse engineering methods on the node's screenshot. The text segmentation algorithm is useful for higher-granularity information about text components, and will be described later in this section.

With pixel reverse engineering methods, such as Prefab, we still can provide similar information to the accessibility metadata even if we reach a dead end in the accessibility tree. In our current prototype, we did not attempt to completely build the hierarchy of UI widgets from pixels using Prefab's method, but we used Sikuli's template matching to find a small set of GUI widgets (e.g. radio buttons, check boxes, sliders) instead. Furthermore, we developed a new algorithm for locating arbitrary text content in a complicated component, e.g. a web view.

A PAX tree is lazily generated on demand. Once parts of it are generated, the results are cached for fast response. The developer can explicitly request the cache to be updated. With proper event hooks that monitor the updates of the corresponding UI, the cache can be updated automatically after the UI is changed. For the reverse-engineered components, the tree can be automatically updated by comparing the consecutive screen shots. Comparing two 1680x1050 screenshots takes only 30ms on a modern PC; therefore, it is feasible to use this technique to continuously monitor the changes of a UI.

In the last parts of this section, we discuss how we have dealt with the challenges mentioned above as well as the text segmentation and detection algorithms.

6.2.3 Determining the Visibility of UI Elements

With only accessibility APIs, we cannot tell if a window or a component is visible or not. To address this problem, our solution is to request the *z-order* of each window from the window manager, and create "masks" to cover the occupied areas of each window from top to bottom. Thus, if a component is not fully covered by the masks and also intersects with its parent's visible bounds, it is visible from the user's point of view.

For virtually visible elements, we only care if a UI element intersects with its parent's bounds. If so, it is virtually visible; otherwise it is invisible.

6.2.4 Region-based Hit Testing

Accessibility APIs usually support hit testing, which is used for getting the accessibility information on a particular point on the screen. Unfortunately, this feature is limited to a single point and a single object.

To get multiple elements in a region, a naïve method is to run the single-point hit testing on each point in that region. However, this is inefficient because a region could have millions of points. Another method is to traverse the component tree and find all visible elements that intersect with the given region. But this is not possible with pure accessibility APIs, because they do not know if a component is visible or not.

Fortunately, PAX already has precise information about the visibility of each UI element. Therefore, PAX provides a function that enables developers to get the internal information of multiple objects in a given region on the screen.

6.2.5 Text Detection and Extraction From Pixels

Current pixel reverse engineering techniques, such as Prefab, can locate common GUI widgets and extract their textual content. However, Prefab's method requires text be located over predictable backgrounds that Prefab can model based on provided examples. If the text is on a background for which Prefab has not been trained, or a complicated background that Prefab cannot model (e.g., a photographic wallpaper), it will not find the text. Recently, computer vision researchers have conducted research on segmentation and recognition methods for small screen-rendered text and reported accuracy achieved of 99.2346% [45, 43, 44]. However, they assumed the position of the text is known and did not address the problem of text detection. To complement these pixel reverse engineering techniques, we have developed a text detection algorithm that locates text in arbitrary position in a screen image.

Given a screen image, the algorithm for converting it to words has three major steps: (A1) segment the image into disjoint blobs of pixels, (A2) merge character blobs into word blobs, and finally apply OCR to extract words.

A1. Salient Component Detection

The goal of this step is to decompose a screen image into a set of salient components, each of which is composed of a blob of foreground pixels. Given a screen image as input, we first convert the image from color to grayscale. We apply an adaptive threshold to filter out low-contrast pixels. Figure 6-3-2 gives an example of the image after this process. Many container widgets such as panels have large areas of plain background pixels that can be

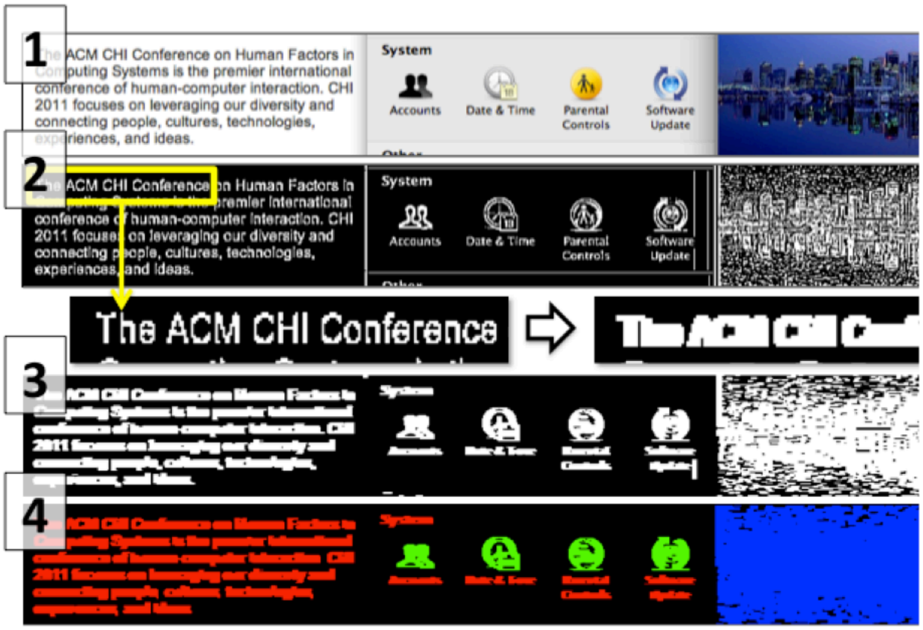

The ACM CHI Conference on Human Factors in Computing Systems is the premier international conference of human-computer interaction. CHI 2011 focuses on leveraging our diversity and connecting people, cultures, technologies, experiences, and ideas.

Figure 6-3: Text Detection process. (1) Given an image, (2) foreground pixels are extracted as small blobs. (3) Blobs are connected to form larger blobs, (4) which are classified into text (red), icon (green), or photo blobs (blue).

easily filtered out in this way. From the high-contrast foreground pixels that are left, we detect long lines that might be window borders or grouping cues. These long lines are then removed so that components close to those lines would not be mistakenly interpreted as being connected by the lines. After this process, text elements turn into a set of blobs, each of which correspond to a character, whereas image elements turn into a set of disjoint parts.

A2. Text Extraction

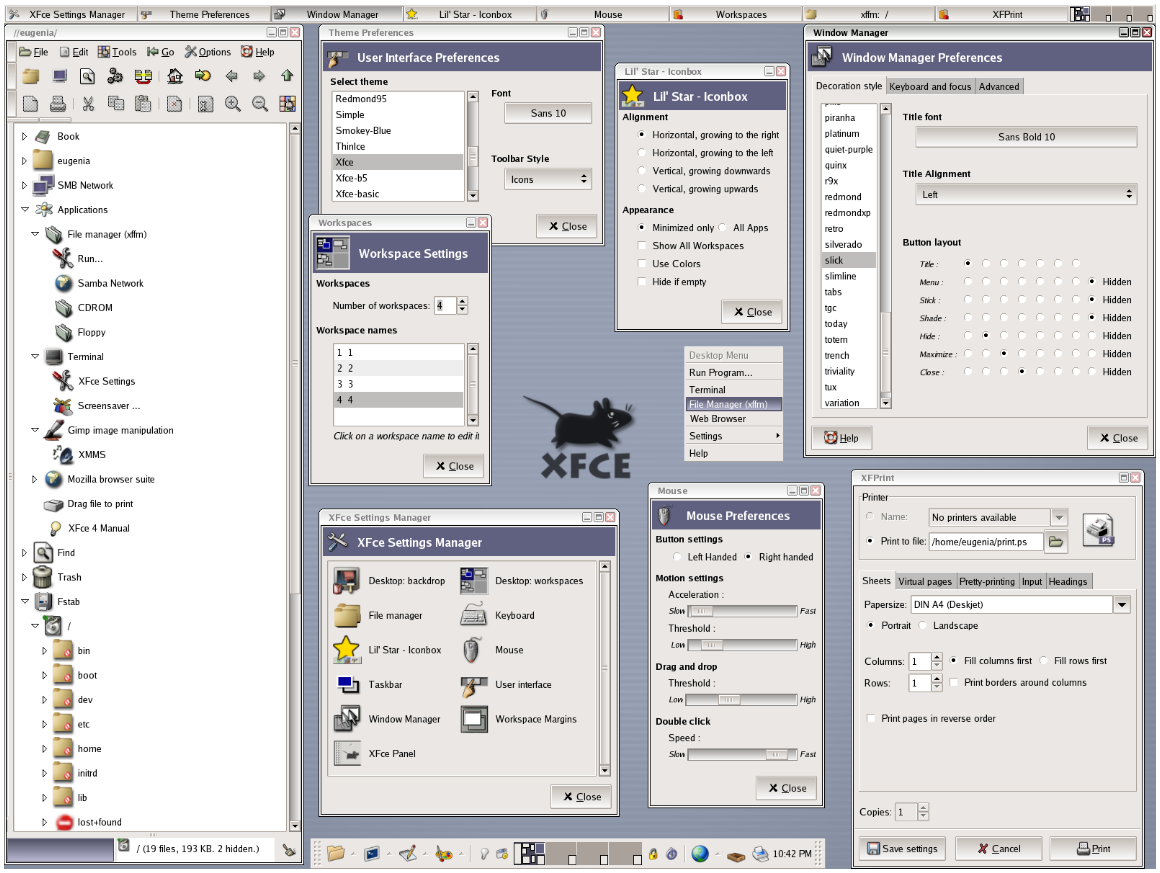
Next, we merge blobs of individual characters into larger blobs of words and use OCR to extract text from each word blob. To merge blobs, we apply a dilation operator to expand the extent of each blob horizontally. If a blob is a character, horizontal dilation will connect it with the characters before and after, as long as the amount of dilation exceeds the amount of character spacing. This spacing depends on the font size, which can be estimated from the height of the blob. Figure 6-3-3 shows the output of this merging process. Then, given a string of connected blobs, we check two properties to decide whether it is likely to be text. First, we check if these blobs share a common height and baseline. Next, we check if the color variation among the foreground pixels is low, since GUI text tends to be rendered in a single, solid color to improve readability. Blobs satisfying both conditions are considered to be text blobs (red pixels in Figure 6-3-4) and passed to the OCR engine to extract words from them.

We did not implement Wachenfeld's screen text recognition algorithms [45, 43, 44], but used the Tesseract OCR engine (http://code.google.com/p/tesseract-ocr/) in our current prototype instead. If it were given the whole screen image as input, the Tesseract OCR engine would perform poorly because it assumes the text is in a single column. (Figure 6-4) If we segment screen images into blocks of words that are processed individually by the OCR engine, the overall performance is better.

6.2.6 Text Image Segmentation Given the Text

The minimum granularity returned by accessibility APIs is one UI component. This may be not enough if developers need the location and the bounds of each individual word or even each character in a text component. Therefore, we have developed an algorithm that segments the image of a text component into individual word blobs. Unlike other text segmentation algorithms, the text string is known from the accessibility API, so we have additional clues to locate each word more accurately. Furthermore, since this algorithm runs on the leaf nodes in accessibility trees, we can assume the text is on a GUI widget with a simple or gradient background for the sake of readability. If the text has a complicated background, our algorithm would not work.

Given that the text is already known (except for some inconsistent cases, e.g. reformatted dates), this problem is not as hard as the original text segmentation problem in OCR. We describe this algorithm in two steps: (B1) segment images into N blobs, where N is the number of words in the given text; (B2) sort and match each blob to its corresponding word in the text.



(a) The screenshot to be recognized with Tesseract-OCR.

```
9 ‘XFmSe\ﬁnqsManiqe| Ir ThemePref2renms |w1MJ uw mam It Lil
tﬂm I I I XFPr|nl [E-
//EHH&n\1/ QE Thama PI&feI&n(&s
_-5'2 Egan H100 “ldlga Kama"; ﬂﬂelp VI USer|me|,facePre
I!|@ $%\1'|'&'.4">*
IIHG \I\I\I.~.~
l>aBzmk
l>.eu!1ema
>iSMBNeMnvk
Q
§
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```

(b) The poorly recognized output from Tesseract-OCR.

Figure 6-4: An example of applying Tesseract-OCR 3.01 to a whole screen image generates very poor results.

B1. Text Segmentation

By assuming the background of the text is a solid or gradient color, we look for a vertical or horizontal line for which each pixel is the same color, in a descendent or an ascendant order in the given region. Once we have found such a line, we create a background by repeating this line to fill the size of the image, and then subtract the original image with this background to get an image with pure text pixels.

We use a top-down approach that is modified from recursive X-Y cut [17] to break a text image into word blobs. We assume the text could be split into multiple lines, but no single word is broken with hyphens. The idea of this algorithm is to calculate the sum of the pixels in each horizontal and vertical line to produce a density graph of white space. This graph shows several peaks that define horizontal or vertical gaps between lines or words, which are also the cut points we need to segment the image into smaller pieces. Our algorithm finds the largest gap, defined by its number of pixels, in the image, and cuts the image horizontally or vertically until the number of pieces remaining equals the number of expected words.

B2. Matching each word with a blob

After the first step, we have N small blobs, each of which corresponds to a word. Next, we sort these blobs vertically and group them into lines with similar baselines. Blobs in a line group are then sorted horizontally to match the writing order of western text.

6.2.7 Matching Accessibility Metadata with What Users See

The *getVisibleText()* method of a *UIElement* should return the text that users see on the screen. One goal of PAX is to deliver the most accurate results. Therefore, we should use the text from the accessibility API if possible. However, the text shown on the screen is not necessary consistent with the one returned by the accessibility API.

A common example is automatic truncation when a string is too long. For example, “my doctoral thesis revision 3.txt” may appear on the screen as “ my doctoral thesis . . . ion 3.txt”. Another example is time and date formation. For instance, “Friday, April 15, 2011

10:48:27 PM ET" could be shown as "Today, 10:48PM" on the screen.

To address this inconsistency, we compare the text from the accessibility API and the text from OCR. If the edit distance between these two strings is smaller than a threshold (20% in PAX, which is proportional to the length of the OCR string), we infer that no inconsistency exists and return the accessibility string as the visible text. Otherwise, when the strings are inconsistent, the OCR text is returned. Note the developer needs to be aware that OCR text could be noisy due to OCR errors. In some cases, the developer does not necessarily need the visible text, which is why we provide *getVisibleText()* and *getText()* for developers to choose according to their scenario.

6.3 Evaluation of Text Algorithms

In this section, we describe the evaluation of our text detection and segmentation algorithms in PAX.

6.3.1 Text Detection Algorithm

To test the performance of our text detection algorithm, we constructed a dataset that consists of six high-resolution screenshots downloaded from the Internet. This dataset covers a variety of GUI widgets and text content on three major platforms (Mac OSX, Ubuntu Linux, and Windows 7). Each word in the screenshots was located and labeled manually as ground truth. The total number of visible words in this dataset is 1141. The number of visible windows is 16. This dataset was held back while we were developing the text detection algorithm; we used screenshots of our own computers for training purposes and preserved this collection only for testing.

During testing, we manually cropped the images of the 16 windows (since window bounds are available in PAX) and applied our text detection algorithm to each image. Our algorithm made 1236 detections. We compared the results to the ground truth and found our algorithm was able to achieve a precision of 84.39% (1043/1236) and a recall of 91.41% (1043/1141). The most common errors were isolated digits that were too small and were

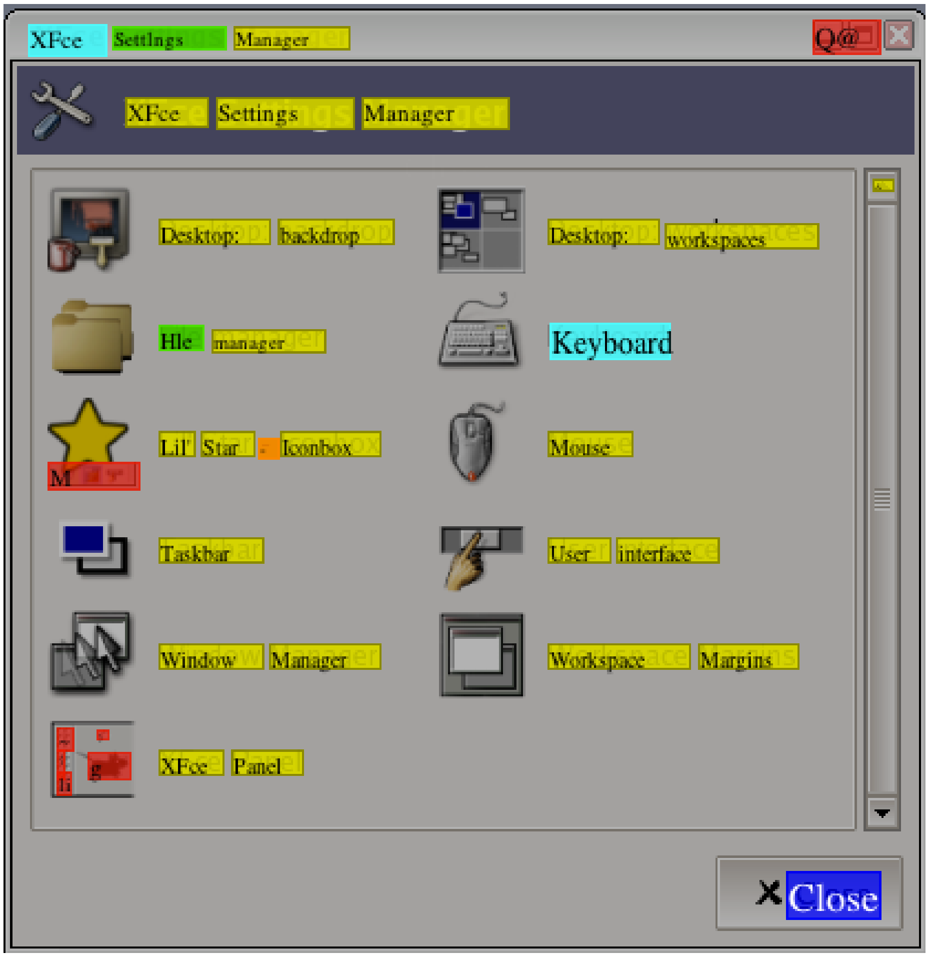
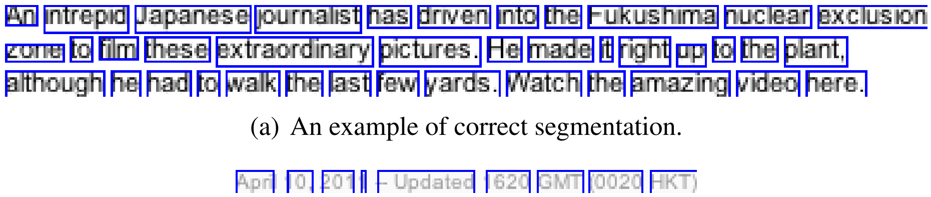


Figure 6-5: An example from the text detection experiment. Red labels are false detection, and the dark blue one is missed. All the other labels are correctly detected, but not necessarily correctly recognized.

repeatedly mistaken by the algorithm as noise for 32 times (2.81%). An example of the testing results can be see in Figure 6-5.

6.3.2 Text Segmentation Algorithm

To evaluate the performance of our text segmentation algorithm, we built a dataset of 331 images each of which is a tightly bound block of text. This dataset was split into training and test sets to prevent overfitting when developing the algorithm. The former has 546 words in 57 images and the latter has 2046 words in 274 images. Each image block has at least two words. These images were collected from our own Mac computers and covered



An intrepid Japanese journalist has driven into the Fukushima nuclear exclusion zone to film these extraordinary pictures. He made it right up to the plant, although he had to walk the last few yards. Watch the amazing video here.

(a) An example of correct segmentation.

April 10, 2011 -- Updated 1620 GMT (0020 HKT)

(b) An example of incorrect segmentation.

Figure 6-6: Two examples show correct and incorrect segmentation results. The failure in this example is caused by the width betwee the two 1's in 2011 is larger than the one betwee "–" and "Updated".

popular desktop applications and web sites (e.g., Microsoft Word, twitter.com, cnn.com). We applied the text segmentation algorithm to each image and manually verified the results. We found only 30 words out of 2046 words were incorrectly segmented, which represents an accuracy of 98.55%. Examples of correct and incorrect segmentations can be seen in Figure 6-6.

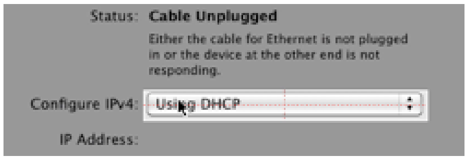
6.4 Validation Through Example Applications

To validate the usefulness of PAX, we present three novel applications enabled by PAX: enhanced Sikuli Script, Screen Search and Screen Copy.

6.4.1 Sikuli Script

Since Sikuli Script was deployed in early 2010, the discussions on its user forum suggest some difficulties of using Sikuli in practice. First, full-screen matching leads to ambiguity and slow performance. Users need an efficient way to constrain the search space to a certain application. Second, screen matching fails if the target window is occluded by other windows. It would be better if the matching worked even when the target window is only virtually visible. Finally, users need a reliable method to read the text from applications and can accept poor OCR results as better than nothing.

To demonstrate the validity of PAX, we enhanced Sikuli Script by addressing the above issues using the system. First, we added a new *App class*, which manages the information about an application and its window. App provides methods to open, close, and switch



Status: **Cable Unplugged**
Either the cable for Ethernet is not plugged in or the device at the other end is not responding.

Configure IPv4: Using DHCP

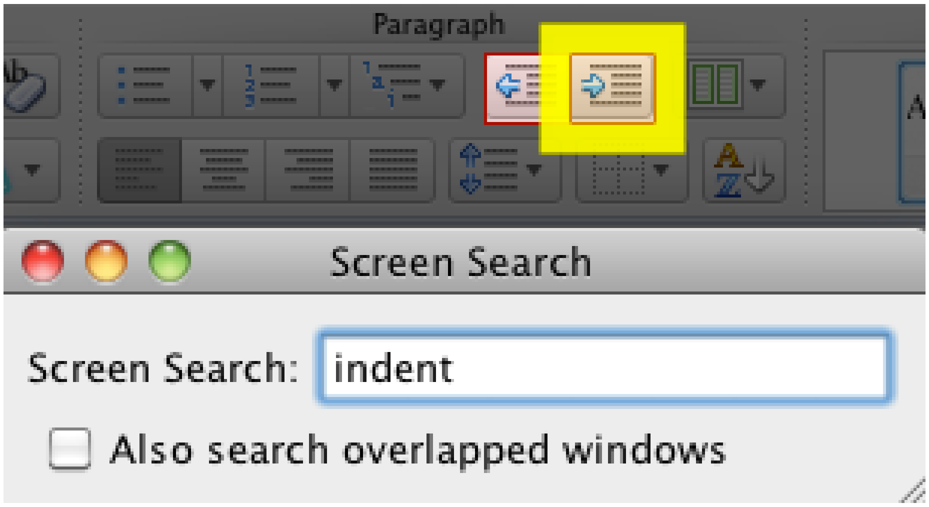
IP Address:

Figure 6-7: As the cursor moves, the boundaries of the target can be identified automatically in Sikuli Script. After the user clicks to capture a screenshot, the XPath to this target is also stored with the screenshot image for future use.

focus to a certain application by giving its name or a disk path. Once an application has opened, the corresponding App instance saves a reference to the *UIElement* of that application. Thus, a user may call *app.window(n)* to get the *n*th window as a Sikuli region and then all subsequent pixel computation can be constrained to this region for improved efficiency. This App class uses applications' accessibility information provided by PAX to enable Sikuli Script to constrain the matching area within an application window dynamically instead of using a fixed region on the screen, and also addresses the performance and ambiguity problem.

Second, we enhanced Sikuli's screen capture interface and searching algorithm with PAX. In the screen capture interface, we use PAX's hit testing to automatically identify the target's boundaries as the mouse cursor moves (see Figure 6-7). A user can simply click on a target to take its screenshot, or use the original method of dragging out a rectangle around the target. When a screenshot is taken, the XPath to the target's UIElement is also saved along with the screenshot (as metadata of the PNG file). Later, when the script is executed, Sikuli Script attempts to find the target with its XPath using PAX first, and then uses the original template matching method if the XPath fails or is unavailable.

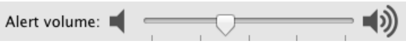
Unlike the first enhancement that requires explicit use, this implicitly speeds up the time spent searching for a target and removes the ambiguity. If the complete XPath is not available, because the target widget does not support accessibility APIs, the enhancement still helps because we can at least know which application the target belongs to and constrain the search within the region of that application. This enhancement also addresses the second issue to allow Sikuli to search virtually visible windows, whose screen content can be seen from PAX even when they are overlapped by others.



Screen Search: indent

□ Also search overlapped windows

Figure 6-8: The two buttons with only image icons “Decrease Indent” and “Increase Indent” can be searched with Screen Search because they have the word “indent” in their accessibility metadata.

Finally, we enhanced Sikuli’s region-based operation by linking each region with the corresponding UIElements and propagating the value and text from leaf components to their logical group. This allows a script to read text from a region or get the value of a component. For example, `find(``)`*.value()* can be used to read the value of a slider. Similarly, text also can be read by *region.text()*. Although PAX tries to unify pixels and accessibility metadata so that Sikuli users can be unaware of PAX, there are some notable differences when using different source of underlying information together. In the slider example we just mentioned, if the slider exists in the accessibility tree, PAX simply returns its absolute value. However, if it does not exist, there is no way to read its absolute value from the pixels. In this case, PAX returns a value between 0 and 1 by measuring the distance from the thumb to the two ends of the slider.

Our enhancements have addressed several practical issues in Sikuli Script. At the same time, the readability and the learnability of Sikuli code are preserved.

6.4.2 Screen Search

Search is a common and important feature in almost every application. However, it is usually limited to the application’s text content. There is no general method to search the

GUI components in a user interface. For example, the text in a text field or in a text area is searchable, but the buttons on a toolbar or the text label on a check box are not. As GUI applications become large and complicated, searching GUI components is especially useful for the users who are not familiar with an interface. For instance, toolbars are widely used in many applications, but the image icons on them are not necessarily easy to understand. In these cases, a user must move the mouse cursor to hover over each button and wait for the tooltip to learn its meaning. The ability to search components by their label or description would be a solution for this problem.

We have created Screen Search as a sample application to demonstrate how PAX can support building new interaction techniques on existing user interfaces. Screen Search enables a user to search not only text but also all GUI components on the screen by keywords.

Unlike the usual search bound to a single application, Screen Search is a global function that searches the content and UI of multiple applications at the same time. Furthermore, it allows a user to quickly navigate or switch the keyboard focus to any components found by Screen Search. In other words, this feature enables the use of a keyboard to navigate a user interface in an arbitrary order. For example, a user can search for “indent” to locate the “Increase Indent” and the “Decrease Indent” buttons on a toolbar, and hit the Enter key to select the highlighted one (Figure 6-8).

Screen Search has two modes: searching only the visible objects (the ones that can be seen on the screen), or virtually visible objects (the ones can be seen or are just objects in the first mode are visible on the screen, we simply highlight them using a yellow box. In the second mode, matched objects are not necessarily visible, so we cannot just draw a box at each position. Instead, we draw a thumbnail of each window that has matched objects in a row and a big preview window with the current selected object. The user can press the Tab key to switch the focus among all matched objects and also bring their parent window to the preview position.

With PAX, the implementation of Screen Search is straightforward because PAX has decided the best source for obtaining the metadata of a component. A naïve implementation is calling *findVisibleChildren* or *findVirtuallyVisibleChildren* of the root of the *UIElement* tree, depending on the search mode, to retrieve the matched components in each window.

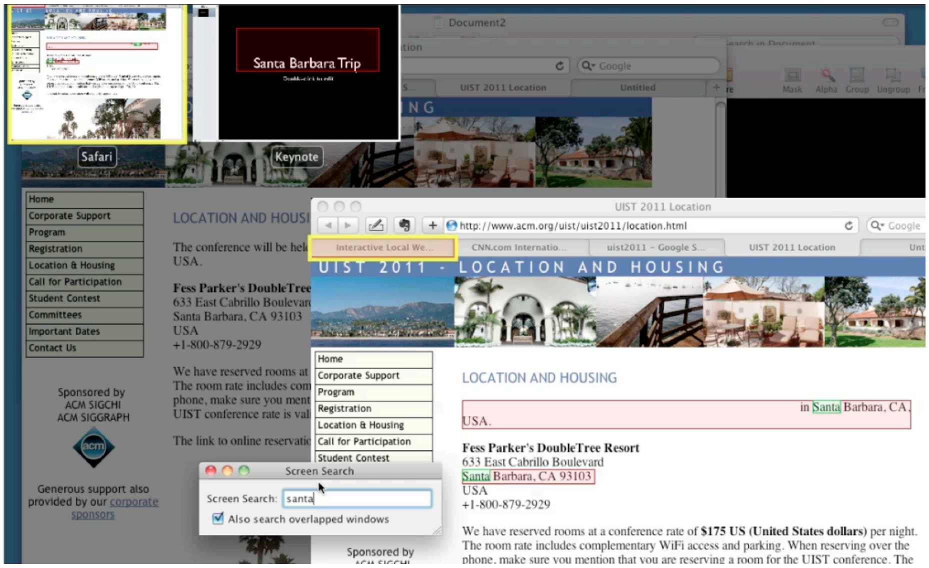


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Figure 6-9: Screen Search finds the given keyword in multiple applications and shows the matched components and their windows at the same time.

However, to support incremental search, we traverse all nodes in the *UIElement* tree and build an index of the text in each node in a background thread periodically. This requires more complexity but provides a better interface that suggests how many and which objects are matched as a user types.

6.4.3 Screen Copy

Screen Copy is a novel application we have built using PAX. Screen Copy allows a user to select a rectangular area on the screen and copies not only the text but also the GUI widgets within that area into the system clipboard. Figure 6-11 shows an example where the interface for setting the appearance on Mac OS X can be copied and pasted into a WYSIWYG HTML editor.

Screen Copy does not simply copy GUI widgets independently, but preserves the hierarchy of widgets and their logical grouping. In the example shown in Figure 6-11, the two sets of radio buttons are correctly grouped together. Thus, only one button in each group can be selected at a time.

Screen Copy is useful for copying an existing interface without its source code and converting it into another format of representation. For example, we could train a library of Flex/Flash widgets using template matching or methods based on machine learning such as Prefab, and then use Screen Copy to convert a Flex/Flash interface to HTML.

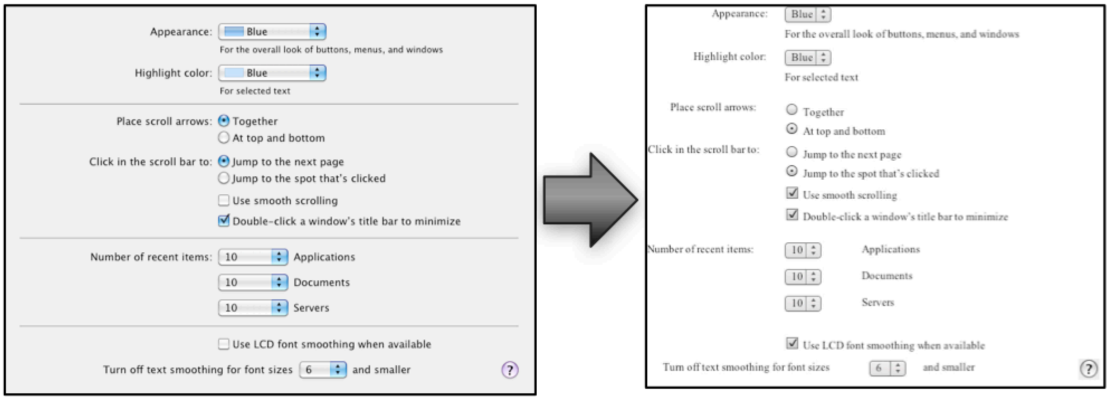
Screen Copy also provides a rectangular selection model to existing programs that only have the common text selection implementation. For example, in a web browser, it is very hard to select and copy any non-text objects, such as a table or a form with pictures. The selection is constrained by the flow of text and the underlying structure of HTML. Thus, one can not easily select only one column of a table or two objects across their different containers. However, these can be achieved with the rectangular selection model provided by Screen Copy (see Figure 6-10).

Screen Copy is straightforward to implement with PAX. Using PAX's rectangular hit testing, the corresponding UIElements within the selected area can be retrieved easily. With the selected objects, Screen Copy transforms each UIElement to HTML tags according to its role and content. Finally, the HTML is copied into the system clipboard and a proper MIME type of the data is set so other applications can then convert it into their own format.

Screen Copy only copies the static interface of an application. It does not copy the dynamic behavior or animated effect on the interface. Additionally, some items that require more interactions to see (such as a drop-down box or a context menu) cannot be copied, so the drop-down boxes in Figure 6-10 were populated with only the one item that was visible at that time. Currently, as a tool implemented to demonstrate PAX, it does not copy widgets that cannot be represented in standard HTML tags. However, in the future, more complex transformations can be implemented to support non-standard widgets.

6.5 Conclusion and Future Work

We have described PAX, a hybrid framework that uses pixels and accessibility metadata to complement each other. We proposed and evaluated two new algorithms for detecting text on screen and segmenting a text image into word blobs assuming the text is known. We validated our framework by implementing three applications: improving Sikuli Script, Screen Search, and Screen Copy. While promising, PAX has several limitations for future



Appearance: Blue
For the overall look of buttons, menus, and windows

Highlight color: Blue
For selected text

Place scroll arrows: ● Together
○ At top and bottom

Click in the scroll bar to: ● Jump to the next page
○ Jump to the spot that's clicked

□ Use smooth scrolling
☑ Double-click a window's title bar to minimize

Number of recent items: 10 Applications
10 Documents
10 Servers

□ Use LCD font smoothing when available

Turn off text smoothing for font sizes 6 and smaller

Appearance: Blue
For the overall look of buttons, menus, and windows

Highlight color: Blue
For selected text

Place scroll arrows: ○ Together
● At top and bottom

Click in the scroll bar to: ○ Jump to the next page
● Jump to the spot that's clicked

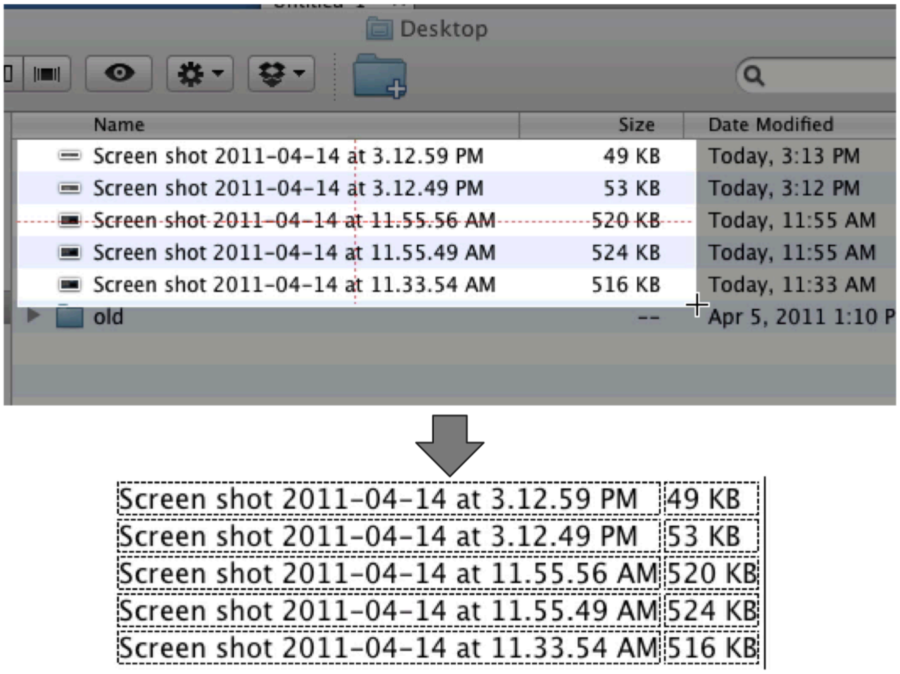
☑ Use smooth scrolling
☑ Double-click a window's title bar to minimize

Number of recent items: 10 Applications
10 Documents
10 Servers

☑ Use LCD font smoothing when available

Turn off text smoothing for font sizes 6 and smaller

Figure 6-10: Screen Copy can be used to select and copy columns of a table or a list view.



Name	Size	Date Modified
Screen shot 2011-04-14 at 3.12.59 PM	49 KB	Today, 3:13 PM
Screen shot 2011-04-14 at 3.12.49 PM	53 KB	Today, 3:12 PM
Screen shot 2011-04-14 at 11.55.56 AM	520 KB	Today, 11:55 AM
Screen shot 2011-04-14 at 11.55.49 AM	524 KB	Today, 11:55 AM
Screen shot 2011-04-14 at 11.33.54 AM	516 KB	Today, 11:33 AM
old	--	Apr 5, 2011 1:10 P

Screen shot 2011-04-14 at 3.12.59 PM	49 KB
Screen shot 2011-04-14 at 3.12.49 PM	53 KB
Screen shot 2011-04-14 at 11.55.56 AM	520 KB
Screen shot 2011-04-14 at 11.55.49 AM	524 KB
Screen shot 2011-04-14 at 11.33.54 AM	516 KB

Figure 6-11: With Screen Copy, one can copy a Mac OS X user interface and paste it into a WYSIWYG HTML editor to create an HTML version of the same interface.

work:

First, in our prototype system, we used template matching to identify GUI widgets from pixels as a proof of concept. The modular design of our framework makes it possible to integrate other powerful pixel reverse engineering methods such as Prefab in the future.

Second, the developers who use PAX need to be aware of the uncertainty due to OCR errors. As future work, more robust OCR algorithms can be integrated with PAX to minimize this uncertainty.

Third, PAX currently uses the accessibility APIs provided by each OS. However, other sources of hierarchical UI representation, such as DOM, can also be integrated nicely with PAX to further improve coverage. For example, on Mac OS X, the built-in browser Safari has implemented a transformation that converts a DOM to an accessibility tree, making this integration possible.

Lastly, PAX currently uses the most common set of accessibility metadata for maximum compatibility on each platform. If more platform-specific metadata and APIs can be used, this opens the door for a diverse body of research. For example, we can add more actions, such as push buttons, or open a drop down menu, to each UIElement, so PAX could be a UI automation framework that automatically uses accessibility APIs or Sikuli Script as its backend. PAX could also support UI customization that provides set methods on each UIElement and draw a customized UI on top of the existing one to show different layout or effects.

Chapter 7

Common Pitfalls and Design Principles

The systems built with the screenshot-driven model are discussed in Chapter 3 to 6. As I described, this model is promising for creating new interaction techniques on any existing UIs. However, while exploring the design of these systems, we found that many users of our systems may encounter some common pitfalls caused by the nature of pixel matching and the screenshot-driven model. As the designers of these screenshot-driven systems, we also faced many challenges while developing them.

For example, once screenshots in Sikuli scripts are taken, the user who writes the script would expect it would work every time in the future. However, the look of the user's desktop changes very often, e.g., opening a new application creates a new window on top of some windows and this may occlude targets in the scripts written by the user. Even scrolling a file list view may stop a script that looks for a specific file icon in that window from working normally.

In this chapter, I discuss the pitfalls we met and also provide design principles as solutions to future designers of such systems. We figure that system designers could incorporate these principles into their design of screenshot-based systems to improve the usability of the systems.

Each design principle is noted with a header as the following, which includes the name and the executor of the principle. The executor could be system designers or users, which suggests who should take care of that principle.

Design Principle: An Example **Executor: system designers or users**

7.1 Invisible Targets

A screenshot-driven technique is, by definition, triggered by taking a screenshot of a *target* object. Typically, this screenshot is later used as an image pattern to match against the whole screen to locate the target. However, while matching the pattern, the target may no longer exist on the screen. That is, it becomes invisible somehow.

The most common reasons that cause this problem are,

- **Occlusion**, there are other windows, applications, or widgets in front of the target;
- **Out-of-view**, the target is in a scrolling view and has been scrolling out of the view, or the target is dragged out of off the screen;
- **Hidden or Minimized**, the target is hidden or minimized due to its nature of design (e.g., dropdown items, menu items, or minimized windows).

Occlusion is a very common problem for Sikuli Script and Test. Opening a new window or bringing a window to the front hide everything behind that window, and therefore cause this problem.

Out-of-view is another common problem. As screen real estate is limited, scrollable views can display a component that is large or has dynamic size depending on its content. Furthermore, the whole screen is also a view in which limits the number of components displayed. When a target is out of a view, it is invisible to the user as well as to screenshot-driven systems.

Finally, a target could be hidden or minimized because it is designed to be capable of these functionality.

We propose two design principles for these two problems.

Design Principle: Dedicated Channel **Executor: system designers**

Sometimes, even a target is occluded by some windows, it is still possible to "see" it through special dedicated channels. For example, Mac OS X accepts an option `kCGWindowListOptionIncludingWindow` in its screen capture API to request the screenshot of a particular window even it is minimized, occluded, or off-screen. For the scrolling-off problem, there are some special APIs for capturing the image of the whole area within a scrolling pane. With those APIs, we can bypass the limitation of the size of the screen and the scrollable view.

Another way to deal with the occlusion problem is to prevent the occlusion in the first place using a dedicated channel that shows only the window containing the target. For example, Virtual Network Computing (VNC), X server, or virtual machines are solutions for creating such a channel. While using Sikuli Script or Test for test automation, a common requirement is to test the system under test (SUT) in a controlled environment that no other windows could cover the SUT. In this case, a dedicated channel such as VNC is a perfect solution.

Design Principle: Scripting — Executor: system designers, users

Scripting is the most general solution requiring no special channels or APIs to the occlusion and the scrolling-off problems. For the occlusion problem, we can script a target by bringing it to the front or moving it to an empty place. Alternatively, we can script the windows on top of the target by minimizing or hiding them. For the scrolling-off problem, we can script the scrolling pane to reveal the hidden areas.

While developing Sikuli IDE, a problem we encountered in the early design phase was that the IDE covered almost the whole desktop so that the user could not take screenshots of the windows underneath it. Similarly, while running a script, the IDE also occlude a large space of the desktop. To deal with this problem, we used this principle to script the Sikuli IDE itself by minimizing it before taking a screenshot and running a script.

In PAX, we add an *App class* to Sikuli Script in order to let the users bring a particular to the front easily. For example, `App.focus("Firefox")` switches the focus to the first Firefox window and brings it to the front. With this command, the user can be sure the

Firefox window is not occluded by other windows.

7.2 Dynamic Appearance

While matching a screenshot, the target may look different over time. The difference may appear in the target itself, or in the surrounding pixels. There are many potential causes of this problem, for example,

- **animation**, the target itself is an animation and changes its look over time;
- **different context**, the target may be moved to a different place than the one where the screenshot of it was taken;
- **different skin**, the skin or the theme of the GUI toolkit may be changed so that the target looks different;
- **different data**, the target may contain GUI components which are populated with different data;
- **different state**, the target may contain GUI components whose states are changed, e.g. being selected or highlighted;
- **environment noise**, the target may be rendered in an environment with noise, e.g. in a photo of the screen.

We propose the following design principles to deal with these problems.

Design Principle: Fuzzy Matching **Executor: system designers, users**

Image matching algorithms play the key role in a screenshot-driven system. As the appearance of the target or its surrounding may change over time, the matching algorithms must be robust against the changes to some extent. In Sikuli Script and Test, we used template matching with correlation coefficients and set a default threshold 0.7 to allow 30%

differences while matching an image pattern. This design allows the user to take screenshots in a sloppy manner, and therefore greatly lowers the barrier to script user interfaces with screenshots. Unlike Sikuli Script and Test, in Deep Shot, we had to use a more sophisticated algorithm SURF as the matching algorithm. The main reason was that we needed to match a photo taken by a camera, rather than a clear screenshot, against the screen. Therefore, we needed to be robust against environment noise, rotation and scaling, and SURF was the best choice given these constraints.

Although system designers can choose the appropriate algorithm for their screenshot-driven systems, the users may still need to adjust *how similar* an image pattern can match by themselves. For example, while writing a Sikuli script, if the user would like to use a sloppily-cropped PDF icon to match all PDF icons on all kinds of backgrounds, it is necessary to lower the similarity threshold of the icon pattern. To simplify this process, we design a preview tool in Sikuli IDE so that the user can adjust the similarity threshold of an image pattern and preview how well it matches the screen. Similarly, if the user expect the pattern to match all the PDF icons in different colors, `.anyColor()` method needs to be called.

Design Principle: Content Understanding **Executor: system designers**

Many GUI widgets are designed to present dynamic text or data to users, e.g. text labels, text fields, drop-down boxes, and menus. These widgets can look very different when they are populated with different data. In some cases, fuzzy matching still can locate the desired target if the image pattern contains sufficient “background pixels” that do not change with data population. However, matching with background pixels could easily cause false positives.

There are some techniques for understanding the content of GUI widgets so that the users can focus on what they really want to find or match on the screen. For example, PAX (Chapter 6) allows a user to locate a GUI widget using the XPath to it in the accessibility tree. Furthermore, PAX also allows one to search a particular widget according to its content or text data.

Optical Character Recognition (OCR) is another technique that can be used for this problem. However, traditional OCR algorithms are not designed for detecting and recognizing text on GUIs. In PAX, we introduced a new text detection algorithm for locating text in screenshots. With this algorithm, we are able to locate the text and then use off-shelf OCR engines with some image processing techniques to recognize them.

7.3 Ambiguity

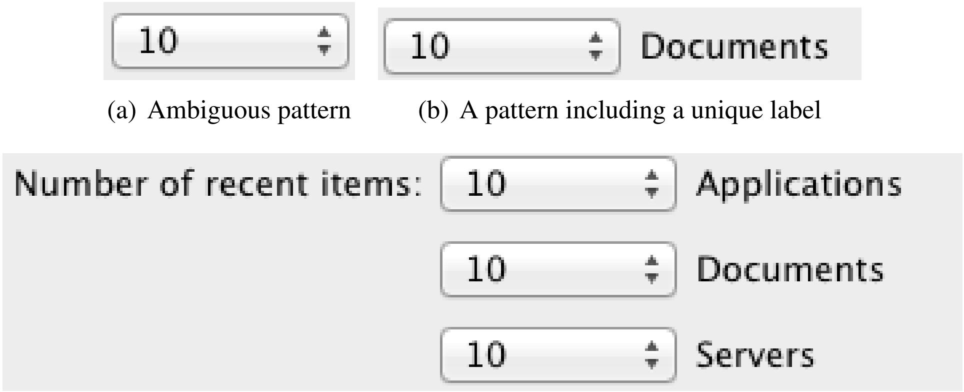
GUI widgets are designed to be used repeatedly so people do not have to learn how to use a user interface from scratch every time. As a result, it is common to see multiple instances of the same widget on a screen. With screenshot-driven systems, users are often confused with this ambiguous situation if they only want to match a particular target.

Design Principle: Constraint on Patterns **Executor: users**

Most ambiguity problems can be resolved by taking a larger screenshot consisting of more pixels. In particular, the user can include a unique label or object in the screenshot to reduce ambiguities while matching. For example, Figure 7-1(a) is a pattern that is too small and can lead to ambiguities while matching against Figure 7-1(c). A better pattern is Figure 7-1(b), which includes a unique label "Documents." In addition to reducing ambiguities, including a unique label in image patterns also makes the pattern easier to understand for the user.

Design Principle: Constraint on Matching Region **Executor: system designers and users**

Besides adding constraints on image patterns, it is also possible to constrain matching areas. For example, with the *App class* we introduced to Sikuli Script, a user can get the boundaries of a particular window and then limit the image matching within that region. A screenshot-driven system can even record which application a screenshot is taken and then match the screenshot only within that application later.



10

10 Documents

(a) Ambiguous pattern (b) A pattern including a unique label

Number of recent items: 10 Applications

10 Documents

10 Servers

(c) The screen that have many drop-down boxes

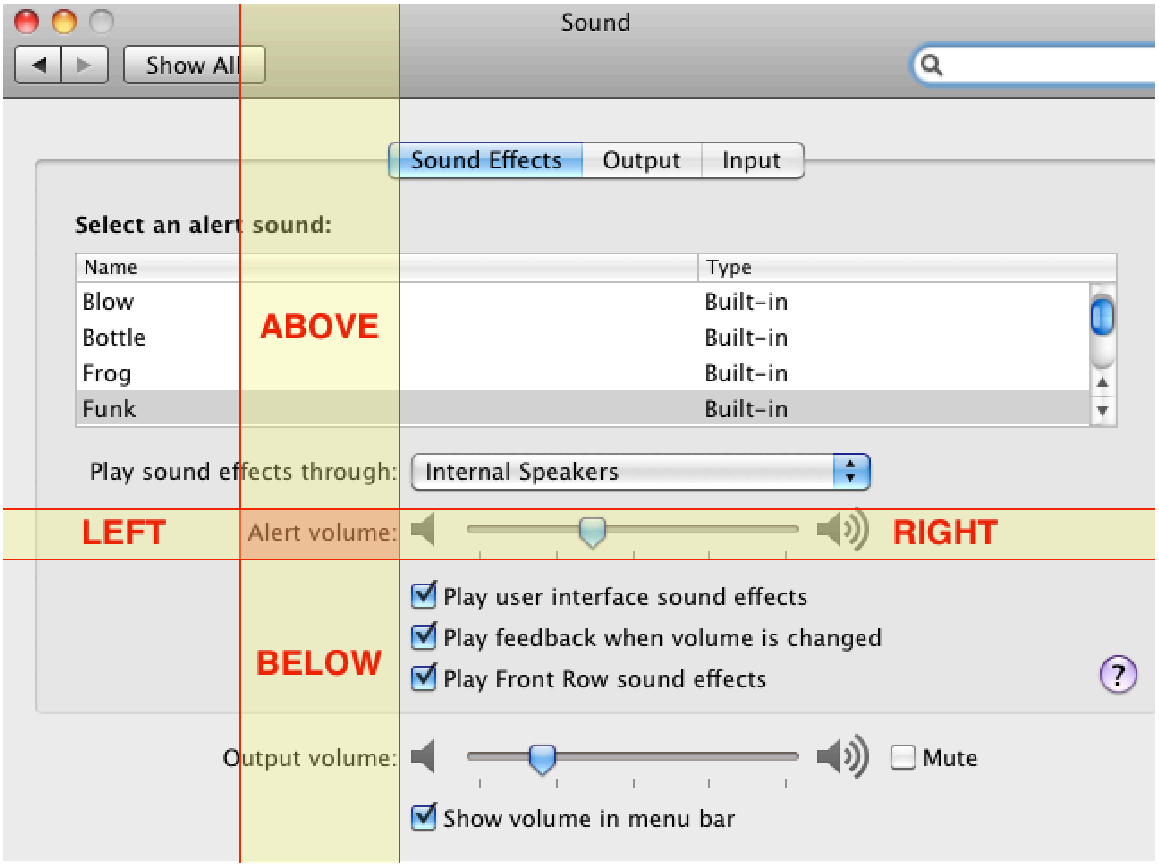
Figure 7-1: Including a unique label in image patterns can reduce ambiguities effectively.

Constraining using the App class prevents external ambiguities, which occur outside of the working application. However, internal ambiguities may still exist. In order to help users to deal with this problem, we designed *spatial operators* to constrain the matching area to a region next to a reference region. For example, in Figure 7-2, there are two sliders that look exact the same. How do we refer to the particular thumb of the "Alert volume" slider? With spatial operators, we use the "Alert volume" label as a pointer, and then use the `right` operator to constrain the matching area within the region to the right of the label. The corresponding Sikuli script command is `find(`Alert volume:`).right().find(`▼`).` Similarly, we can also use `above`, `below`, or `left` to specify the corresponding regions.

7.4 Self-Ambiguity

We have described that ambiguities can be caused by many GUI widgets that look the same. Sometimes ambiguities may come from the target itself in different states. For example, when a widget is disabled and grayed out, it may still look very similar to itself in the normal (enabled) state. With the fuzzy matching algorithms we described earlier, the algorithms may mistakenly find the disabled one using a pattern in the normal state. In addition to the enabled/disabled states, *focus* and *selection* could also cause this problem.

Design Principle: Exact Matching **Executor: users**



Select an alert sound:

Name	Type
Blow	Built-in
Bottle	Built-in
Frog	Built-in
Funk	Built-in

Play sound effects through: Internal Speakers

Alert volume:

☑ Play user interface sound effects

☑ Play feedback when volume is changed

☑ Play Front Row sound effects

Output volume: □ Mute

☑ Show volume in menu bar

Figure 7-2: Spatial operators are used to constrain matching regions.

Fuzzy matching is suitable for most cases in screenshot-driven systems. However, to match GUI widgets in a particular state, the system should use exact matching algorithms instead of fuzzy ones. Although a screenshot-driven system can provide both the exact and the fuzzy matching algorithms, the user is still responsible to tell the system which one to use depending on his/her intention.

In Sikuli Script and Test, we use fuzzy matching as the default algorithm. At the same time, we also provide a method `.exact()` in the *Pattern* class for the users to specify if they want the image pattern to be matched in an exact manner. Besides this, the users also can raise the similiarity threshold of a very high value using the preview dialog in Sikuli IDE (Figure 3-6) to distinguish between different states of the widget.

7.5 Conclusion

In this chapter, we have discussed four common pitfalls in screenshot-driven systems, which include invisible targets, dynamic appearance, ambiguity, and self-ambiguity. We also provided various design principles for system designers and users to overcome these problems.

Chapter 8

Conclusion

In this thesis, I have presented the notion of using screenshots as visual references in user interface design and the interaction model driven by screenshots. I also described the potential applications, frameworks and algorithms to facilitate the interaction driven by taking screenshots.

For the applications, I have described how I applied the screenshot-driven model for the Sikuli project, which includes searching documentation and GUI automation using screenshots. Based on Sikuli Script, I described a GUI testing system for GUI developers and QA testers to verify GUI behavior without writing code. Except for augmenting the interaction within a computer, I described Deep Shot, which expands the screenshot-driven model to task migration across multiple devices.

For the frameworks and algorithms, I have described PAX, which is a hybrid framework that associates the visual representation of user interfaces and their internal hierarchical metadata. This framework augments the existing pixel-based systems and allow them to access the pixels as well as the internal structured data of a user interface. To build PAX, I also described two algorithms: 1) a text detection algorithm that locates text in arbitrary position in a screen image; 2) a text segmentation algorithm that segments the image of a text component into individual word blobs given the underlying text string is known.

Finally, we identified common pitfalls in screenshot-driven systems and provided design principles for system designers or users to deal with them.

There are many promising future directions for further exploration on this topic.

Visual Memory

Nothing would ever be forgotten after seeing it once if we have photographic memory, whether it is an important number, date, image, or phrase. With modern computers and software technologies, it is possible to record screen pixels continuously and make them searchable. In Sikuli Search, we have explored searching a collection of documents using screenshot. We can further extend this notion to search information along the time dimension. For example, we can search a particular web page or document we have seen by text or images. We also can search and restore old configuration settings that broke something accidentally.

Creating Automation Scripts with Block Programming and Screenshots

In Sikuli IDE, we introduced using screenshots as first-class objects in a textual script editor. However, it is still difficult for novices to write a script in a text editor without syntax errors. One solution for this is to further extend the scripting environment to a visual programming editor, for example, a block programming user interface in Scratch [29]. With this way, a user can drag a desired command block out of a palette and drop it into other blocks to form a sequence of commands.

Annotation on Existing User Interfaces

With the screenshot-driven model we described, it is possible to let users create annotations on existing user interfaces using screenshots. One application of this is for creating contextual help on any GUI. Yeh et al. [50] have initiated building a tool to support users with common computer skills to create contextual help. An extension of this idea could be automatically converting tutorials consisting of screenshots into Sikuli-style scripts that create contextual help on actual user interfaces.

8.1 Summary

To conclude, this thesis has introduced a new notion of using screenshots as visual references and an interaction model driven by taking screenshots. I presented many applications that embody this notion as well as their common pitfalls. I hope to inspire others to explore this new area of research and find out more potential applications based on this idea.

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