Bonfire: A Nomadic System for Hybrid Laptop-Tabletop Interaction

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ABSTRACT

We present *Bonfire*, a self-contained mobile computing system that uses two laptop-mounted laser micro-projectors to project an interactive display space to either side of a laptop keyboard. Coupled with each micro-projector is a camera to enable hand gesture tracking, object recognition, and information transfer within the projected space. Thus, Bonfire is neither a pure laptop system nor a pure tabletop system, but an integration of the two into one new nomadic computing platform. This integration (1) enables observing the periphery and responding appropriately, e.g., to the casual placement of objects within its field of view, (2) enables integration between physical and digital objects via computer vision, (3) provides a horizontal surface in tandem with the usual vertical laptop display, allowing direct pointing and gestures, and (4) enlarges the input/output space to enrich existing applications. We describe Bonfire's architecture, and offer scenarios that highlight Bonfire's advantages. We also include lessons learned and insights for further development and use.

ACM Classification Keywords

H.5.2. [**Information interfaces and presentation**]: User interfaces—*input devices and strategies*. I.5.4 [**Pattern recognition**]: Applications—*computer vision*.

General terms: Design, Human Factors, Algorithms

Keywords: Laptop, tabletop, surface, micro-projector, computer vision, object recognition, gestures, peripheral display, extended display, tangible bits, ambient interaction.

INTRODUCTION

For well over two decades, computer systems have sought to escape the confines of the screen, mouse, and keyboard [39]. Only recently have hardware systems matured to the point where this is feasible. Projectors are now bright enough to project clearly onto variegated surfaces, and recent micro-projectors are small and light enough to be held or even worn [21]. Today's tiny cameras are inexpensive and provide high-resolution images at high frame rates. Laptops have outpaced desktops in sales, and now have sufficient computing power and battery life to enable long work hours in public places, including those where free WiFi has become the rule rather than the exception. There is more interest and participation in "nomadic computing" than ever before, and, at last, the resources to support it. It is therefore fitting for research to explore new ways of enriching computer use in these nomadic circumstances, which are quite unlike the traditional office workplaces where many early tabletop systems began (e.g., [41]).

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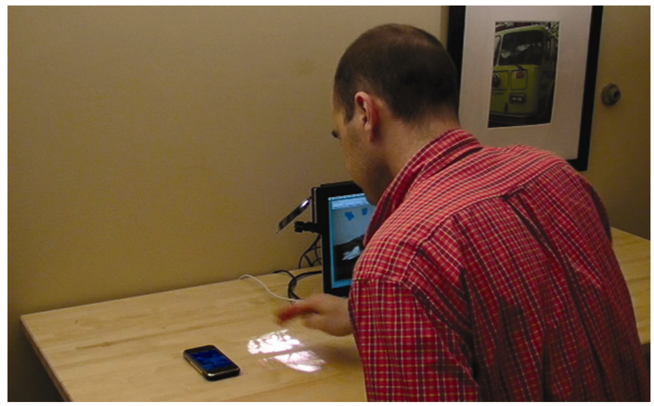

Figure 1. The Bonfire system consisting of a laptop with two mounted laser-based micro-projectors, two cameras, and custom software for integrating them.

In this paper, we present *Bonfire*, a nomadic hybrid laptop-tabletop system (Figure 1). Laptop computers are ubiquitous, and tabletop systems are beginning to emerge commercially; research exists pertaining to both types of systems. Somewhat surprising, however, is the lack of exploration at their intersection. Although some projects have allowed interactions between laptops and interactive tabletops [28,29,42], these arrangements have focused on extending the tabletop experience, and were anchored in one place by the non-portable tabletop systems. In contrast, Bonfire is a self-contained, portable, nomadic computing system weighing little more than a laptop alone. It is designed for those who "camp out" in coffee shops, libraries, and informal meeting spaces. Bonfire attempts to combine the advantages of the laptop's screen, keyboard, and computing power with the natural input, extended space, and object-awareness of projected and perceived peripheral displays. While tabletops lack the high input bandwidth afforded by a keyboard and mouse, and laptops lack surfaces for sketching, gesture, peripheral display, and sensing physical objects, together these devices can augment each other in useful ways and ameliorate each other's weaknesses. By integrating micro-projectors, Bonfire provides a large interaction space without significantly increasing the laptop's size and weight, as with recent multi-display laptops.

The following scenario illustrates the rich, nomadic interactions that Bonfire could enable. Jane, a college student, takes her Bonfire-equipped laptop to her favorite coffee shop on a Saturday morning to complete a lab report for botany class. When she opens her laptop, Bonfire's two mounted cameras capture the table, loading settings to automatically adjust the projection to the surface. Jane places her mobile phone on the table beside her laptop, and digital photos from a recent nature hike "spill" out from the phone onto the table. In one brush of the hand, she moves them to her laptop. She puts on headphones and taps the play button on a music player projected on her laptop's other side. When Jane sets her coffee next to the laptop, Bonfire recognizes the cup and opens a spreadsheet detailing how much money Jane has spent in the last month on coffee. A second spreadsheet graphs her caloric intake. Later, a friend stops by, so Jane removes her headphones to say hello, placing them on the table within Bonfire's view. Conveniently, Bonfire pauses the music, which it resumes once Jane picks the headphones up from the table. Later, Jane needs a figure from a botany textbook in her report, so she places the book in Bonfire's view. With a press of a button, the image from the book is captured onto her laptop, where it appears in her Word document.

The above scenario makes use of four key advantages of Bonfire's hybrid laptop/tabletop configuration, which we have identified as a result of this exploration. Bonfire (1) can observe the laptop periphery and respond appropriately, e.g., to the natural placement of objects within its field of view, like the headphones, (2) enables the interaction between physical and digital objects via computer vision, (3) provides a horizontal interactive surface along with the laptop's vertical screen, allowing direct pointing, sketching, and gestures, and (4) extends the input/output space to enrich existing applications.

The remainder of this paper presents Bonfire's system architecture and components, including a discussion on its use of computer vision. It also offers usage scenarios that illustrate more of Bonfire's capabilities. Our scenarios describe how Bonfire provides *appropriate ambient response*, in which the system senses the user's state without explicit interaction and "does the right thing." Bonfire takes important initial steps in exploring the intersection of laptops and projected interactive surfaces, all within a self-contained nomadic setup.

RELATED WORK

Research related to Bonfire can be divided primarily into four categories: projection-based smart spaces, mobile device projection systems, tabletop systems, and physical/digital interaction. Due to limitations of space, we cannot provide a comprehensive treatment here; only the most relevant pieces are discussed.

Projection-Based Smart Spaces

Projection-based "smart spaces" use fixed projectors and cameras to create interactive surfaces, usually in an office environment. Perhaps the most well-known system is Wellner's DigitalDesk, a pioneer in this space [40,41]. The Augmented Surfaces project by Rekimoto and Saitoh [28] integrated wall, table, and laptop displays, allowing the movement of information between them. Two years later, the EnhancedDesk [17] showed how finger tracking, paper, and digital representations can be unified with computer vision and infrared light. Similar to these projects, Bonfire's augmented interaction takes place on a desk, table, or other horizontal surface and includes interaction with paper documents, and tracks hands. By integrating into the body of a laptop, Bonfire offers portability that was missing from these earlier systems.

While smart spaces have typically focused on creating large interactive spaces, other systems have used cameras or projectors to extend the interaction space around a PC. DeskJockey [51] used a fixed projector to project widgets in the space around the PC, which could be interacted with using a proxy window on the PC screen, but which were not directly manipulable. Other systems have used cameras [49,50], infrared sensors [6], and acoustic sensors [15] to enable gestural interactions in the space around the device. Prior research from Letessier and Bérard [18] combined hand tracking with projected interfaces. Bonfire extends the idea of interacting in the space around a device by combining rich gesture-based and object-based interaction with direct projected feedback.

The Everywhere Display (ED) project [24] used steerable projectors to create projected interactive surfaces on multiple surfaces in a single room. A subsequent version, ED-lite [23,33] , switched from using a fixed setup to using a laptop and a portable projector. However, unlike Bonfire, ED-lite did not enhance activities on and around the laptop, and instead focused on extending the computer display to surfaces around the laptop.

Wilson proposed an early mobile smart space with his PlayAnywhere system [43]. PlayAnywhere offered projection coupled with hand, paper, and object recognition, and supported a wide range of tabletop applications using a relatively small projection configuration. However, while mobility was part of PlayAnywhere's vision, mobility and nomadic computing were not central in its usage scenarios or physical design. In contrast, Bonfire demonstrates how a mobile smart space system can enhance the mobile computing experience specifically.

Mobile Device Projection Systems

With recent advances in projection technology, a growing number of commercial and research systems offer mobile, often handheld projection-based interactive spaces. Many projects in this area involve users standing and pointing a handheld or worn mobile projector at a wall, making the resulting interactions quite distinct from those in Bonfire. Examples are the projects by Beardsley et al. [3], Cao and Balakrishnan [8], Cao et al. [9], and Mistry et al. [21]. Raskar et al. [26] used radio frequency tags (RFIGs) in combination with a handheld mobile projector to discover information about objects in the environment. While these systems use mobile projectors, they do not enhance use of laptops in nomadic settings as Bonfire does.

Some recent work has explored interactions with *simulated* mobile device projectors. Examples for mobile phones are by Greaves et al. [12] and Hang et al. [14]. In both cases, simple interactions with maps and photos were the focus. Another example is the Hotaru prototype [32] that simulated a sharable PDA projection with which two people can interact. PenLight [30] used a fixed projector for augmenting interactions with diagrams and paper documents, but proposed a mobile version using a projector integrated into a pen body. Collaboration with mobile projectors was addressed in the CoGAME cooperative game [16], where teammates guided a robot with projected displays. A Wizard-of-Oz study of an even smaller form factor was carried out by Blasko et al. [5], who studied simulated wrist-worn projection displays (e.g., projection from a wristwatch). Bonfire is distinct from these investigations in that it leaves user's hands free to interact among two projected displays and the laptop between them. By using currently available micro-projectors, we explore real-world interaction issues with nomadic projection-based systems.

Tabletop Systems

There has been much work in the last decade on horizontal tabletop systems. Two of the earliest working tabletop systems were DiamondTouch [11] and SmartSkin [27]. The StarFire video prototype [36] was an early vision of both horizontal and vertical interactive display surfaces, a vision still not fully realized today. Recently, systems such as DiamondTouch [11] and Microsoft Surface[1] have become commercially-available. Different interaction paradigms have been explored on tabletops, from those based on physical simulation [1,44], to those based on hand gestures [46,47]. Bonfire combines hand gestures with object recognition. Since it is intended to be used with a laptop, we do not attempt to provide an extensive gesture grammar.

Physical/Digital Interaction

Prior research has extended tabletop interactions through the use of physical objects. Augmented Surfaces [28], UbiTable [29], and weSpace [42] combined tabletop interactions with documents on personal laptops. Other systems have allowed for interactions with everyday objects. Systems such as [2] and [38] recognized tagged objects to retrieve documents, while metaDESK [37] used inert physical widgets to interact with a surface projection. Such systems typically recognize objects using visual tags [2,37], RFID [22], and Bluetooth [45]. Bonfire uses visual object recognition to recognize untagged objects, and can augment these objects with displays, widgets, or information presented on the laptop screen. Bonfire can also respond appropriately to user state inferred from objects that appear, such as a cup of coffee placed on the table, or headphones or eyeglasses set down by the user.

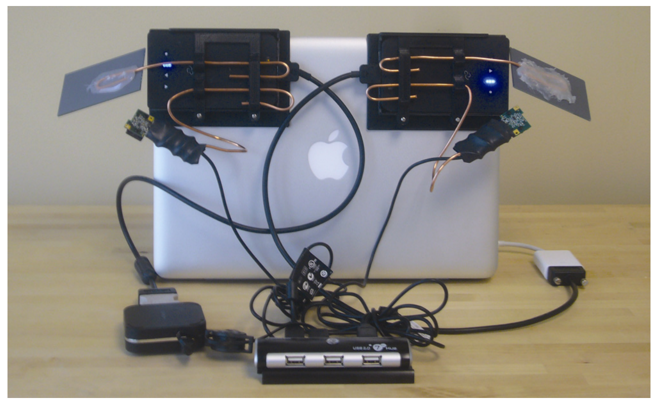

Figure 2. Rear view of the Bonfire prototype hardware setup. Projectors and cameras are mounted on the laptop screen and connected via a USB hub. Mirrors reflect the projected images to the sides of the keyboard.

BONFIRE ARCHITECTURE

At the core of Bonfire are micro-projectors and cameras integrated into the screen of a laptop, and software components that support sensing and capture of user action around the laptop. Our current system runs on an Apple MacBook with a 2.4 GHz processor, 4GB RAM and a 13-inch display. This section describes the hardware and software implementation of our prototype system in detail.

Hardware Components

To demonstrate the vision of a nomadic laptop/tabletop hybrid system, the Bonfire system includes a micro-projector on each side of the laptop, and a pair of cameras, each observing user actions and objects in the projection space. (Figure 2 shows the setup as seen from the rear of the laptop).

Bonfire uses two Microvision[2] Pico Show projectors. These tiny projectors use laser-scanning technology rather than a lens, providing an image that is always in focus (compared, for example, to the 3M LCD-based projector that we had

[1] Microsoft Surface. http://www.microsoft.com/surface

[2] Microvision, Inc. http://www.microvision.com

used initially). In addition, the Microvision projectors provide a relatively bright image, an important factor for our system since it is intended to be used under varying lighting conditions. The cost of a Microvision projector is expected to be around $400-$500 once they reach production. The projectors we use are pre-production units acquired for research purposes.

Bonfire observes user action and objects in the projection space using a pair of Logitech Quickcam Pro 9000 webcams, each associated with a single projector. In order to reduce the footprint of the cameras and to increase mounting options, we removed the cameras' original casings. Finally, the cameras and one of the two projectors are connected to the computer via a small, powered USB hub and the laptop's VGA input, while the other projector is connected through an EVGA UV Plus USB external graphics adapter.

To provide the experience of embedded micro-projectors and cameras into the laptop's display, we created special mounts that attach to the back of the laptop's screen (see Figure 2). Each camera-projector pair is mounted and a mirror is used to direct the projected image to the side of the laptop. These mirrors will become unnecessary once the projectors are physically embedded in the screen's frame. The components are shown (disassembled) in Figure 3.

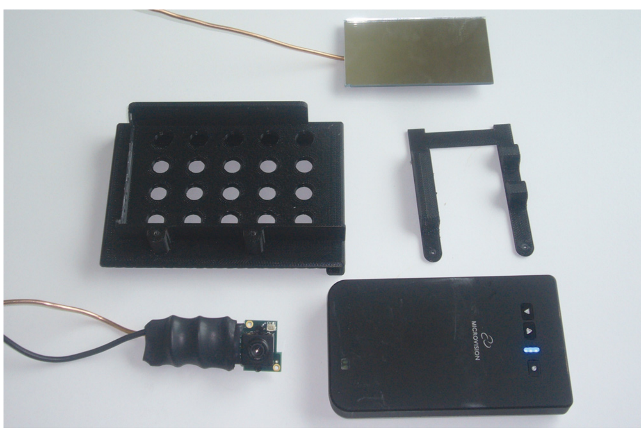

Figure 3. Custom-designed projector and camera mount. Mounts were printed using a Dimension Elite 3D printer. Counter-clockwise from top: Mirror, custom projector mount, Logitech webcam, Microvision[2] pico-projector, and a fastening bracket.

Once mounted, and with Bonfire running, a projection-calibration step is required to correct the distorted image. Bonfire's projection area is significantly affected by the height of the laptop's display (the system configuration presented in Figure 1 includes a laptop display with a height of 8.94"). Furthermore, since projectors are meant to be physically embedded in the screen's frame, we were also constrained in the volume that the projection components can occupy, preventing, for example, the use of multiple reflections. Automatic projector calibration using camera-based computer vision techniques has been described in prior research ([24,48]). Bonfire corrects projection distortion by computing the homography between the distorted projection, the camera image, and the table surface using the technique described by Sukthankar [34]. This allows us to pre-distort the projected image so that it appears correct to the user. In our prototype, the user configures the system by clicking on the four corners of the projection area in the camera view displayed on the laptop, and then clicking on the four corners of a piece of paper with known dimensions placed on the table. This configuration is stored between uses, but must be repeated if the laptop screen is tilted significantly from its position.

User Input and Object Recognition

Bonfire uses computer vision techniques to recognize objects in the projection space and to track hands and gestures on the table. These techniques were implemented using the Intel OpenCV computer vision libraries and Python 2.5. Here we describe the processing stages used to analyze images and recognize objects and gestures.

Adaptive Background Subtraction

To identify objects on the tabletop, we first perform background subtraction on the camera image. Bonfire uses a mixture of Gaussians to model the background [31]. During start-up, Bonfire captures its current view and classifies it as background. Regions that differ from the reference background image are classified as foreground objects. The mixture of Gaussians method may be used in different lighting conditions without any special configuration, and adapts to gradual lighting changes over time, such as the changing light from a window. Bonfire uses an adaptive method to determine whether an object remains in the foreground, to handle cases where the user places items on a surface without intending them to be processed by the vision system. Each time a new object appears in the foreground, Bonfire attempts to recognize it. If the object is not recognized, Bonfire incorporates the object into the background. This allows the user to place an item on the table, such as a book or newspaper, without occluding future interactions in the projection space. Bonfire retains a list of these unrecognized objects in case the user later wishes to use them, e.g., to import as a figure in a paper, or to serve as a visual-search query.

User Input Recognition

Tracking Fingers

Bonfire users can interact with the projected surfaces using their hands. Bonfire employs a color-based skin detection algorithm (Figure 4). In each frame, Bonfire computes a color histogram for each foreground object. (Other methods for detecting fingers are also possible, e.g., template matching [17].) We have found this color-based metric method to be effective at identifying hands. However, because skin color can vary between users and in different lighting conditions, Bonfire captures an image of the user's hand at startup and uses it throughout the session. Once the user's hand is identified, Bonfire uses geometric features to identify individual fingers. Using a method from prior work [20], Bonfire calculates both the convex hull and convexity defects in the hand image. Fingers are identified as points on the convex hull that are separated by defects. Bonfire computes a cursor position for the projected surface based on the user's hand shape: if a single finger is extended, that point is used as a cursor. Otherwise, the cursor is calculated as the midpoint of the extended fingers, allowing users to interact with display objects using multiple fingers, as recommended by prior work [46].

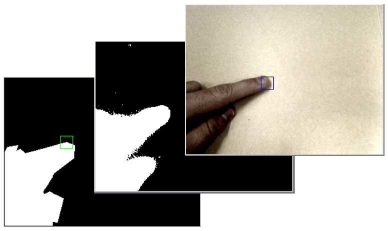

Figure 4. Finger tracking. The hand is identified in the foreground image based on a color histogram. The shape of the hand is analyzed and coordinates of the finger position are computed.

Tapping, Dragging, Flicking, and Crossing

Bonfire supports four manual input methods for interacting with the projected surface: tapping, dragging, flicking, and crossing.

Tapping, Recognizing touch-based events typically requires some method for detecting when the user's hand contacts the surface. Because of the shallow angle of the Bonfire cameras, and our desire for the system to be usable in a variety of lighting conditions, we have avoided infrared- or shadow-based tracking systems (e.g., [43]). Other research has suggested the use of microphones [41] or acoustically-coupled sensors [15]. Our original prototype used a microphone to detect taps, but we found that environmental noise caused a large number of false positives. Instead, Bonfire detects taps using the laptop's on-board accelerometer, which is a common feature in many new computers. Bonfire monitors the accelerometer readings, and registers a tap when the accelerometer reading is greater than a threshold, determined automatically at startup based on current levels. This accelerometer-based tap detection is not falsely activated by loud sounds, although other actions, such as the user typing, can generate these events. For this reason, Bonfire only recognizes a tap event when it detects both an accelerometer event and when the user's finger is near a target in the camera view.

Dragging. Bonfire allows users to drag items across the surface. Because the accelerometer cannot detect passive contact with the surface, Bonfire uses a gesture to drag items. The dragging gesture begins by tapping the surface, followed by dragging two or more fingers across the surface. This gesture causes draggable projected objects to follow the user's hand. A drag ends when the user closes his hand or reverts to pointing with a single finger. This gesture is supported by prior work [46] which found that users often drag virtual objects with two or more fingers.

Flicking. Users can perform a flicking gesture by rapidly moving their finger across the surface in some direction [47]. Bonfire uses the accelerometer to detect the start of a flick, and the camera to track the direction. To maximize detection accuracy, our flicking motion detection is currently limited to the cardinal directions.

Crossing. Finally, Bonfire supports interacting with on-screen targets through goal crossing. Crossing is detected by tracking the user's finger as it travels across the surface and through interactive elements. Crossing provides an alternative selection method when tapping cannot be easily detected, such as on an unstable surface.

Object Recognition

In addition to touch and gesture interaction, Bonfire supports additional interactions through the recognition of physical objects placed on the table. In contrast to other systems such as [2] and [38], our system allows recognition of untagged objects using computer vision. Recognized objects serve two purposes within the Bonfire system. First, users can perform *explicit interactions* with objects, such as placing a document within a projected area in order to scan it. Second, recognized objects can be used to support *implicit interactions* by collecting information about the user's current state. For example, recognizing the user's headphones on the table indicate that the user is not wearing them, and therefore cannot hear their output.

Currently, Bonfire uses a simple object recognition algorithm based on color histogram matching [35]. First, the background is subtracted from the captured frame as described earlier. Next, we find the connected components within the image and compute an RGB histogram for each foreground object. Finally, we attempt to match each component to a known object through correlation of the histograms. This method is sufficient for disambiguating small sets of known objects, but would not be adequate for recognizing a wide array of objects. (In the future, we intend to incorporate a feature-based object recognition method.) As hinted earlier, our object-recognition component is implemented as an open-world model. An open-world model allows objects to be classified as "unknown", while a closed-world model will always classify an object as one of a set of known objects. If an object is classified as "unknown", its presence is recorded but its pixels are incorporated into the background.

INTERACTION WITH BONFIRE

In this section, we describe different aspects of enhanced interaction that become possible with Bonfire and that fit the nomadic nature of laptop use. Rather than replicate previous "smart space" scenarios, we invented these scenarios to demonstrate how Bonfire can extend the mobile computing experience in typical nomadic-use environments: at home, at work, and at a coffee shop. Our examples and illustrations are organized into two main interaction themes. The first theme leverages physical objects to augment and extend interaction with the system. These scenarios range from using detected objects to maintain awareness of the user's state, to augmenting the user's interaction with objects through projection and tracking. The second theme focuses on creating interactive spaces on the surfaces around the laptop, with the goals of enriching peripheral and situational awareness and enhancing interaction with computing applications.

Our prototype fully supports Bonfire's interaction methods, including gesture tracking and object recognition. We have not yet completed all work to connect Bonfire to external data sources (e.g., Facebook, mobile phones, etc.).

Augmented Interaction with Physical Objects

One of Bonfire's key benefits comes from its ability to recognize physical objects in the immediate vicinity of the laptop. Here we describe a number of examples that demonstrate how this capability can create rich interactions.

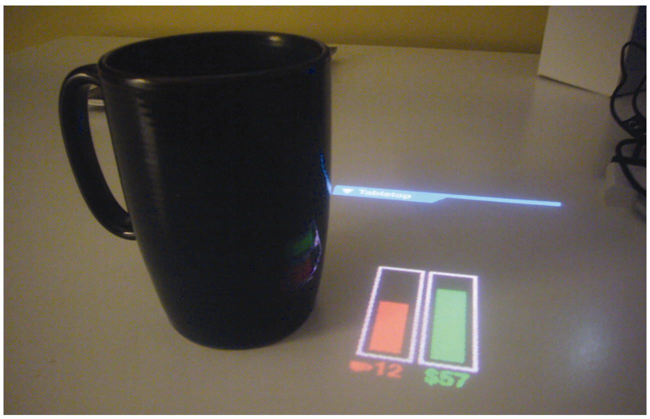

Figure 5. Augmenting interaction with physical objects. After the coffee cup is detected, Bonfire projects a graph of cups of coffee consumed and an approximate cost this week. When the user taps the graph, a detailed view is shown on the laptop screen.

Tracking Use of Everyday Objects

Many people are interested in tracking their use or consumption of everyday objects, whether for financial, fitness, environmental, or other purposes. Rather than requiring users to log every use of a specific item, Bonfire can detect the presence of an object in its working area, and can track and report use of that object over time. For example, a person who is concerned that they are spending too much money at a café might use Bonfire to track their coffee consumption. When the user places a coffee cup on the table, the cup is automatically recognized (Figure 5). Bonfire projects a chart of recent coffee purchases on the table next to the cup, allowing the user to see her coffee expenditure at a glance. Tapping the chart opens a more detailed chart on the laptop screen. This feature could also be used to share information about an object with a social networking service such as Facebook or Twitter.

Objects Trigger Appropriate Ambient Response

Bonfire uses information about the objects around the user to enable subtle interactions. When Bonfire detects an object being added or removed from the table, it can adjust the settings of laptop applications or of the projected space. In our first example, a user is wearing her headphones and listening to music on the laptop when a friend stops by. The user takes off her headphones and places them on the table. Bonfire recognizes the headphones and sends a command to

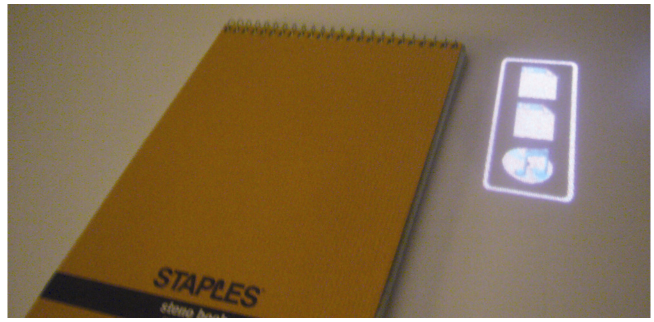

Figure 6. Physical bookmarks for digital tasks. When the notebook is detected on the table, Bonfire projects a list of applications that were open when the notebook was last seen.

pause the music. In our second example, a user takes off his glasses and places them on the table. Bonfire recognizes the glasses and increases the font size on the computer to allow the user to keep working. Bonfire's ability to infer the state of the user through objects around the laptop can be easily used to create seamless interaction.

Physical Contextual Bookmarks

One advantage of Bonfire is its ability to observe both computer activity and objects in the proximity of the computer. This ability can be used to provide links between computer tasks and the physical objects that they require. Bonfire maintains a list of applications that are open on the laptop, and associates this list with objects detected on the table. This list could be used to suggest or automatically launch applications when that document reappears. Consider a student who wants to continue their work on a project. When the student places her notebook on the table, Bonfire detects the notebook and projects a list of applications and documents that were open when the notebook was last seen (Figure 6), allowing her to resume the task more easily. Bonfire could also allow users to explicitly link physical objects with digital resources, as in [2] and [38].

Augmenting Cross-Device Interaction

Bonfire's ability to recognize objects could also be used to share information between devices in a natural and immediate way. For example, Bonfire is able to detect a mobile phone in the projection area. Using a system like BlueTable [45] to pair the phone with the laptop would enable transferring photos or other information between the phone and laptop. Bonfire provides a photo browser widget, allowing users to scroll through and view a list of photos, and "flick" photos to send them to the computer (Figure 7).

Capture and Use

Finally, Bonfire allows users to capture and import the image of an object on the table (Figure 8). This capability is useful for submitting visual-search queries, for personal logging, or when writing a document. Bonfire locates the object in the foreground, and uses its calibration information to automatically de-skew the image. Bonfire then uses a system-wide scripting language (currently AppleScript) to insert the image into the active program, such as an e-mail message or word processing document. While Bonfire typically uses a lower camera resolution for performance reasons, it will switch a camera to its maximum resolution when capturing an object.

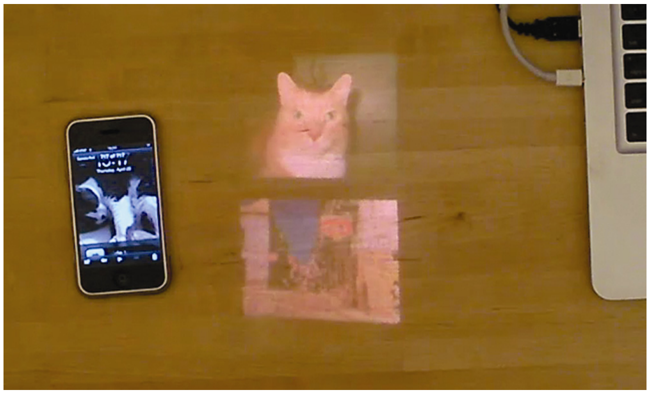

Figure 7. Photos from the phone are projected on the surface. The user can save a photo to the laptop by "flicking" an image in the direction of the laptop.

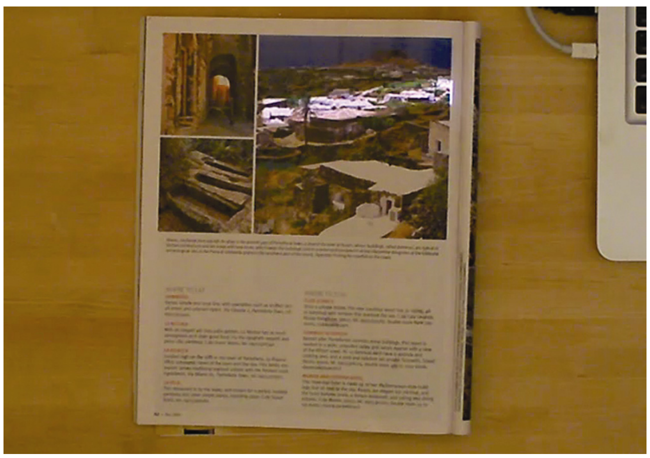

Figure 8. The image of an object on the table can be captured and imported for use as a visual-search query, or as a figure in a document. An animated scan-line (shown) provides feedback.

Enabling Rich Computer Interaction

Clearly, the addition of two interactive displays to a laptop provides new opportunities merely by expanding screen real estate. Additionally, having two projection areas on either side of the keyboard allows users to perform secondary interactions on the tabletop while their dominant hand is using the laptop's keyboard or touchpad.

Peripheral and Contextual Displays

The availability of projected areas to either side of the keyboard makes Bonfire perfect for providing peripheral awareness when the user's focus is on the laptop screen. In fact, we found the placement of projection areas directly to the left and right of the keyboard extremely comfortable for a glanceable peripheral display. Similar to previous systems, e.g., SideShow [7], and consistent with findings from prior research on multiple display use [13], we illustrate the use of Bonfire for maintaining awareness of other people or for keeping track of location-relevant information.

Bonfire provides a notification screen, called the dashboard, where peripheral information can be displayed. The dashboard appears when the user has not actively used the projected display for several minutes, and it can also be summoned manually. This dashboard can be used to project contextual information, such a status changes posted by contacts on Facebook (Figure 9). Since the quality of projected text is low, Bonfire favors graphical information, and directs text-rich information to the computer screen. In the current dashboard display, active contacts' profile photos are presented in a grid. Visual flashes around these icons indicate user activity. Tapping on a contact's icon opens the corresponding Facebook page on the laptop's screen. Bonfire could also use knowledge of its location to deliver location-specific peripheral awareness, such as real-time bus arrival information.

Augmented Interaction Space

One of Bonfire's basic uses is to provide a display and interaction space for less frequently used tasks such as music playback. To demonstrate this, we created a widget to control music playback that can be placed in Bonfire's projection area. Similar to prior work [10], which enabled interaction with media through gestures alone, Bonfire uses the projection area to display the currently playing song, the upcoming song, and directions for performing the gestures.

We created a second example widget, inspired by prior work in peripheral displays [19], that uses the projection space to display thumbnails of frequently viewed webpages. Bonfire detects when the web browser window is active, and automatically displays the list of thumbnails. The user can then tap on a thumbnail to load the specified webpage in the browser. We have implemented this widget for the Firefox web browser. The current prototype uses a fixed list of sites, but could be extended to capture sites from the user's browser history or a web-based bookmarking service.

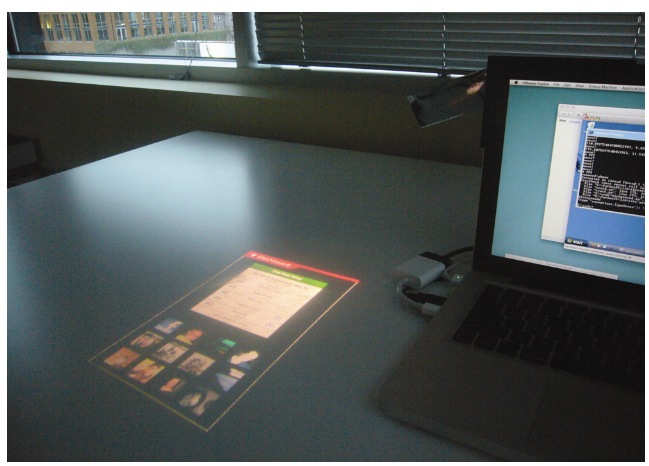

Figure 9. Bonfire's dashboard presents peripheral information. This display shows real-time bus arrival information for a nearby stop from the local transit authority, and shows a grid of photos to keep the user aware Facebook contacts' activity.

Finally, Bonfire has the potential to enrich entertainment activities such as gaming. While many current laptop computers provide fast processors and powerful graphics cards, they are still limited by the size of the screen. Bonfire allows a richer gaming experience by providing a greater display space. Massively Multiplayer Online Role-playing Games (MMORPGs) are prime candidates for using this feature, as they typically provide a lot of information on the screen. Figure 10 illustrates the use of Bonfire for playing the game World of Warcraft with the laptop screen used for 3D world navigation and player-to-player communication, and projected displays showing a map view on the left and player inventory on the right. This setup allows the player to focus on primary game tasks while remaining aware of overall game state. Although the peripheral displays are not currently interactive for World of Warcraft, they could be used to enable additional interactions, such as tapping inventory objects to use them, or performing a gesture to cast in-game spells.

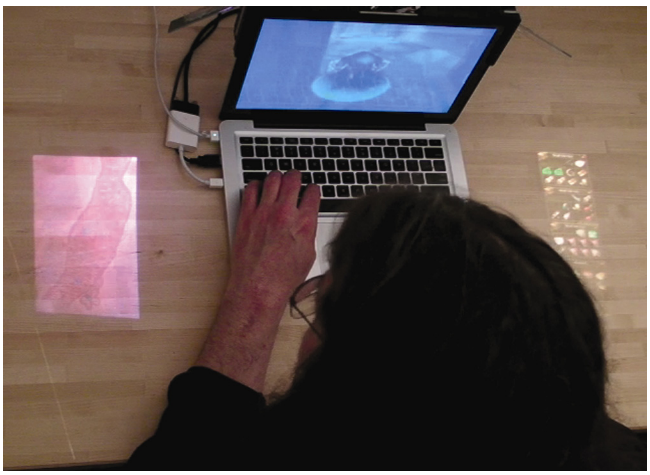

Figure 10. Enhancing MMORPG game play. The laptop screen is used for 3D world navigation and player-to-player communication. Map view and player inventory are shown in the projection areas.

REFLECTIONS

In this section, we describe insights we obtained while creating and interacting with Bonfire. These include reflections related to the physical integration of Bonfire into the frame of a laptop, and to the physical and social contexts within which Bonfire may be used.

In designing Bonfire, our focus was on augmenting laptop use in environments that vary in their physical characteristics and lighting. Not surprisingly, variations in lighting and surface material affect both the recognition and projection systems. We mitigate the severity of these challenges using a combination of three approaches. First, our system aims to adapt automatically to changing conditions, e.g., through adaptive background subtraction. While we currently use the camera input to perform adaptation, future versions could include dedicated sensors for detecting the surface material, as seen in prior research [15], or could even adapt based on location. Second, in cases for which automatic adaptation is insufficient, we aim to provide lightweight, user-driven calibration steps (e.g., hand-color training). Finally, a suitable choice of graphical and textual elements and color schemes can help make Bonfire's projection visible even under difficult lighting conditions. In the future, we intend to enable automatic adaptation of contrast and color scheme to produce the best results under changes in ambient lighting.

One of our biggest initial concerns was that the limited height of the laptop's screen would render the projection area too small to be usable. Indeed, the height of the screen, and thus the projector, imposes strong geometric constraints on the available projection area. We were pleasantly surprised to find just how satisfying the interaction with Bonfire is, even with these constraints. As can be seen in the figures throughout the paper, even on a smaller 13" laptop, Bonfire is able to support the full range of interactions described in this paper (without modifying the micro-projectors themselves).

Through the iterative design of the physical construction of Bonfire, we have gained a number of insights important for the design of embedded projection units used in systems such as Bonfire. The desire to achieve the largest possible projection area adjacent to (and not behind) the laptop's keyboard, imposes significant constraints on the design of embedded projection systems. First, the spread of the embedded projector needs to be wide to project a large image, i.e., such that the image size grows at a high rate as it moves away from the projector. It is clear that, while projection units such as those used in the Microvision pico-projectors are small enough in size, systems such as Bonfire will benefit greatly from projection units targeted for this specific style of projection.

Finally, we believe this work raises interesting questions about how systems such as Bonfire will be used in public spaces. Bonfire's projected surfaces are oriented toward the user, but are easily viewable by others. This means that information, previously only visible on the laptop screen, may now be publicly projected. Physical privacy filters are available for laptop screens, but cannot be used on projected surfaces. This issue has not been addressed in our current implementation of Bonfire, but could be addressed by differentiating public and private views, as demonstrated in prior research [4,29].

FUTURE WORK

We envision several possibilities for enhancing Bonfire. Future versions of Bonfire could leverage additional cameras or other sensors to learn more about the user's activities. For example, the user-facing camera found in many current laptops could be used to enable gaze tracking. This feature could be used to present notifications where the user is currently looking, or to estimate the user's current state. Augmenting Bonfire with a depth-sensing camera system would allow us to create a 3D reconstruction of objects and hands in the projection area. This reconstruction could be used to project onto non-planar objects, as demonstrated by prior research [25], or to track the user's hand in 3D space to enable gestural interactions similar to those implemented in PlayAnywhere [43].

Finally, one area of great potential is in using Bonfire to enhance co-located collaboration. Bonfire's collaboration ability could be enhanced by adding a third, forward-facing projector, or by making Bonfire's current projectors steerable. We are now implementing gestures that enable the user to reorient the projections on the sides of the laptop to face a person sitting across from them. Even more exciting is the possibility of overlapping the projection areas of multiple Bonfire systems. Similar to prior work with handheld projectors [9], we plan to explore the possibilities for control, sharing, and collaboration that emerge from overlapping camera and projection views.

CONCLUSION

We have presented Bonfire, a self-contained nomadic system that enriches user interaction through projection and computer vision set into the frame of a laptop computer. Through its ability to recognize objects and track user actions, Bonfire enables the system to be aware of its user's state from objects, affords augmented interaction with objects around the laptop, and offers a rich interactive display suitable for peripheral and contextual displays. While laptops lack the ability to sense physical objects, provide peripheral awareness, and support for gestures and sketching, and while tabletops lack the high input bandwidth of a keyboard and mouse, together, such systems augment each other in new and exciting ways. Tabletop systems no longer need to be confined to dedicated spaces, but can travel with laptops to enhance any space.

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