Fiberio: A Touchscreen that Senses Fingerprints

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ABSTRACT
We present Fiberio, a rear-projected multitouch table that identifies users biometrically based on their fingerprints *during* each touch interaction. Fiberio accomplishes this using a new type of screen material: a large fiber optic plate. The plate *diffuses* light on transmission, thereby allowing it to act as projection surface. At the same time, the plate *reflects* light specularly, which produces the contrast required for fingerprint sensing. In addition to offering all the functionality known from traditional diffused illumination systems, Fiberio is the first interactive tabletop system that authenticates users during touch interaction—unobtrusively and securely using the biometric features of fingerprints, which eliminates the need for users to carry any identification tokens.

Author Keywords
Touchscreens; multitouch; user identification; fingerprints.

ACM Classification Keywords
H5.2 [Information interfaces and presentation]: User Interfaces. Input devices & strategies.

INTRODUCTION

Several researchers have proposed techniques that allow interactive tabletop systems to distinguish users during interaction. The ability to associate each touch with a particular user has allowed such systems to personalize interaction [21], log user activity [2], and ensure that only the authorized users can access private objects [31] or perform privileged activities [6].

A number of existing approaches address this challenge. Unfortunately, they either require users to carry identification tokens, such as RFID tags [28], rings [30], or marker gloves [21] or they can only distinguish among a small group of users, for example by recognizing their shoes [29], their hand contours [31], or the chairs they sit in [6].

Researchers have therefore pointed to fingerprint recognition as a possible solution to the problem. Fingerprint-based authentication is secure [20] and—in conjunction with touch interaction—would be unobtrusive for users. First steps in this direction include a separate fingerprint scanner placed *next* to the touchscreen [32] and an interactive fingerprint scanner without a screen (Ridgepad [15]). These prototypes point out the challenge in designing such a

Figure 1: *Fiberio* is a rear-projected tabletop system that identifies users based on their fingerprints *during each interaction*—unobtrusively and securely. The shown application uses this to verify that the respective user has the authority to perform the current activity, here approve invoices above a certain value. The key that allows Fiberio to display an image *and* sense fingerprints at the same time is its screen material: a fiber optic plate.

system, i.e., to sense fingerprints and display a computer-generated image *in the same space at the same time.*

This challenge boils down to two contradicting requirements with respect to the screen material. On the one hand, the screen has to reveal fingerprints, i.e., produce contrast between the ridges and valleys of the fingerprint. Known solutions require a *specular* screen surface to accomplish optical fingerprint scanning. On the other hand, to be used as a display, the screen has to allow the rear-projection to produce a visible image, which requires the screen material to be *diffuse*. Unfortunately, specular and diffuse are contradictory requirements for such a surface.

These contradictory requirements eliminate a number of candidate technologies that appear suitable at first glance. Tabletops based on frustrated total internal reflection [13], for example, cannot generate the contrast between fingerprint valleys and ridges and thus do not afford scanning users' fingerprints with sufficient quality.

In this paper, we demonstrate how to resolve this contradiction. We present Fiberio, a multitouch table that recognizes fingerprints during touch interaction. As shown in Figure 1, Fiberio authenticates users while interacting with the table.

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FIBERIO

Figure 2 shows Fiberio's hardware configuration, which is essentially a *diffused illumination* [22] setup: a 19″ screen ("diffuser"), a projector that rear-projects onto the screen, an infrared illuminant that illuminates the screen from behind, and cameras that observe touch input on the screen.

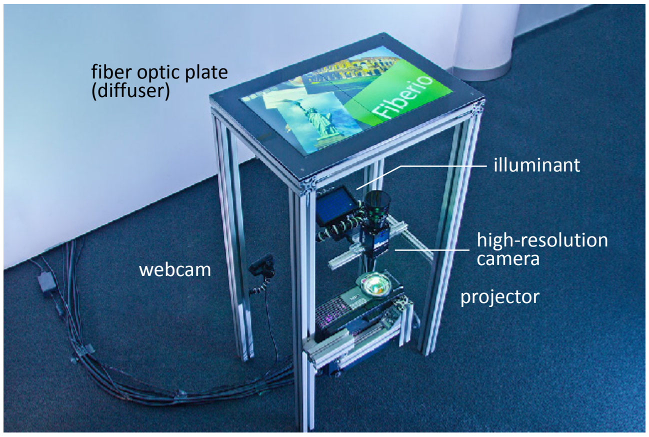

Figure 2: Our *Fiberio* prototype is a standard diffuse illumination setup, except that the diffuser is a fiber optic plate.

What distinguishes Fiberio from a regular diffused illumination setup is the nature of the diffuser: At first glance, Fiberio's diffuser appears like a sheet of frosted glass, but it is a 3mm thick, 4233dpi fiber optic plate. Its 40 million optical fibers run perpendicular to the surface and transmit light between the top and the bottom of the screen. Such plates, typically marketed for shielding CCD sensors from X-ray radiation in medical applications, are being produced in large numbers today and we repurpose them without modification in our prototype.

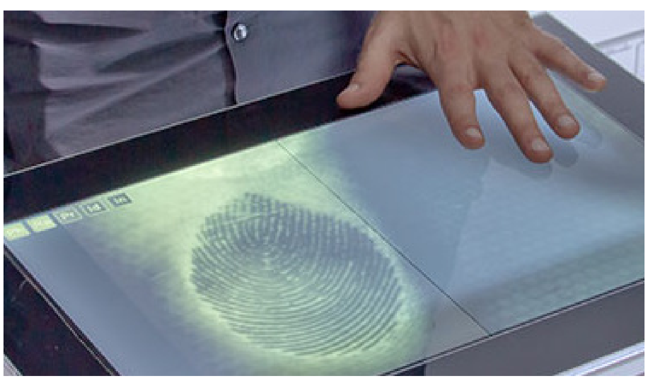

Figure 3: Fiberio displaying a region of its high-resolution raw input image, revealing the user's fingerprint.

In Fiberio, this fiber optic plate resolves the aforementioned contradiction. As we describe in detail in the section "working principle", the fiber optic plate (1) diffuses light on transmission. This causes the light coming from the projector located below the screen to scatter, allowing users to see the image on the surface from all locations around the table. (2) With the correct illumination setup, the fiber optic plate creates a specific type of specular reflection: *frustrated Fresnel reflection*, which is different from the type of reflection used in FTIR-based tabletop systems. This setup causes the infrared light that illuminates the plate from below to produce a visible contrast between fingerprint ridges and valleys, which allows the high-resolution infrared camera below the table to capture fingerprints (Figure 3). Because of the fiber optic plate, Fiberio is capable of *simultaneously* displaying images and capturing fingerprints.

Example Scenario: Collaborative Approval of Invoices

Since Fiberio identifies users during touch interaction, it supports a wide range of applications that require *secure* authentication. Figure 4 shows one of the examples we have implemented. A bank clerk and his manager approve invoices by pressing the 'pay' button on each invoice. When the invoice exceeds the clerk's approval limit as shown in Figure 4a, Fiberio refuses the transaction until (b) the clerk asks the manager to (c) approve the invoice. He does so by pushing the same button the clerk had pressed. This time, however, the transaction is performed under the manager's credentials, verified against his higher approval limit, and approved.

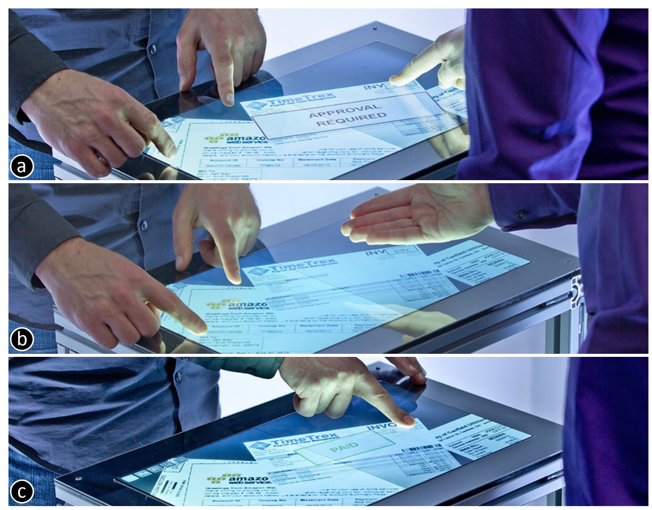

Figure 4: Example scenario. A bank manager (left) and clerk (right) approve invoices. (a) When the clerk encounters a bill above his approval limit, Fiberio refuses the payment. (c) The manager completes the transaction, pushing the same button.

Fiberio enables this scenario by authenticating users during each touch interaction and, in this scenario, by retrieving their approval limit from a database. Fiberio does so by authenticating users based on their fingerprints—integrated seamlessly into regular interaction. Fiberio thereby avoids the need for login procedures or identification tokens.

CONTRIBUTION

The main contribution of this paper is a prototype multi-touch table that identifies users biometrically on every touch interaction—securely and unobtrusively. We achieve this ability by capturing fingerprints *and* displaying a computer-generated image at the same time on the same surface, thereby implementing technology whose existence has been hypothesized since the late nineties [32]. Our solution is based on a new type of screen material, i.e., a fiber optic plate. We also demonstrate fingerprint processing at interactive rates (21ms processing time per frame) and a demo application in which Fiberio continuously authenticates users during interaction.

RELATED WORK

Fiberio is related to optical tabletop systems, applications of glass fibers, user identification, and fingerprint sensing.

Optical tabletop systems

Fiberio primarily inherits properties from diffused illumination systems, such as Holowall [22] and the Microsoft Surface table [25]. Such systems capture the light reflected by objects through their diffuser to detect touch or recognize fiducial markers. The diffuser such systems typically use, however, blurs all the details of the user's finger as well as those of objects above the surface [4].

Applications of glass-fiber bundles in HCI

A number of systems in HCI have exploited the capability of optical fibers to transmit light. For example, FiberBoard integrates optical sensing into a small form factor by folding the optical paths of its camera system [18]. Lumino channels light through tangibles, thereby allowing tabletop systems to sense stacked objects [4]. $FuSA^2$ projects color effects onto a large plastic fiber bundle and uses the same fibers to sense hovering hands [26].

User identification

To achieve reliable user authentication on tabletops, researchers have typically equipped users with identification tokens, such as rings that flash unique sequences of light (e.g., IR Ring [30]) or using fiducial markers to produce touch input (e.g., attached to a glove [21]).

Other approaches eliminate the need for such tokens, but in exchange are limited to identifying users only within a small group of users. Such approaches include identifying users based on the color of their shoes (Bootstrapper [29]) or the contours of their hands (HandsDown [31]). Capacitive touchscreens may identify two stationary users based on their electrical impedance after calibration [14].

Finally, a series of tabletop systems are able to *distinguish* users that simultaneously interact with the table. For example, DiamondTouch electrically connects users' chairs to the surface of the tabletop, closing a circuit when a user touches the table [6]. While this associates a user around the table with each touch contact and thus distinguishes users reliably, this approach is limited to a small number of stationary users. Other systems have associated touch events with users around the table by tracing their arm to the edge of the table using the reflections of the user's arm above the tabletop (e.g., [35]) or by instrumenting the table with sensors to capture users' arms and bodies around the table (e.g., Medusa [2]). Note that while these last systems reliably *distinguish* users, they do not *identify* them.

In contrast, Fiberio builds on fingerprint identification, which allows users to be authenticated unobtrusively and securely during each interaction.

Fingerprint recognition

Fingerprints are widely used for biometric identification feature, because they exhibit unique patterns of structural features that make such authentication reliable [3, 20].

Researchers have *simulated* interactive fingerprint-based devices, such as to invoke finger-specific functions [21,32]. Researchers have also directly used fingerprint scanners to control the mouse cursor (e.g., as relative [9] or absolute touchpad [1]) or for detecting gestures [12]. In our previous work, we used fingerprint recognition to improve touch accuracy (Ridgepad [15]).

To incorporate such high-resolution fingerprint sensing into touchscreens, in-cell technology has been hypothesized to one-day capture the diminutive structure of fingerprints. In-cell screens place photocells between screen pixels, allowing touchscreens to perceive the reflection from structure above the display. Sharp showed an image of a fingerprint captured on a small 2.6″ touchscreen using in-cell technology and VGA input resolution [5], but it is unclear if the quality and resolution sufficed for processing. Samsung ships a 40″ in-cell touchscreen (Microsoft PixelSense [25]), though with only ~27dpi input resolution, i.e., a factor of 20 too low for high-quality fingerprint scanning. Future in-cell systems may or may not offer the size and resolution required for reliable fingerprint scanning at 500dpi [20].

While in-cell screens afford scanning fingerprints, scanners achieve the highest contrast by optically sensing the specular reflections on polished waveguides.

BACKGROUND: OPTICAL FINGERPRINT SENSING

In order to record fingerprints, a camera needs to produce sufficient *contrast* between a fingerprint's ridges and valleys. Existing diffused illumination systems do not produce this contrast, because the skin of the user's finger diffusely reflects light and because the system's diffuser further blurs those reflections, thereby discarding all the structural details [22].

Prism-based fingerprint scanning yields excellent contrast

As shown in Figure 5a, prism-based fingerprint scanners achieve excellent contrast by shining light through a light diffuser and into a large solid glass prism [34]. (b) Since the light hits the top surface at an oblique angle, any blank part of the surface reflects the light directly into the camera, causing such areas to appear bright. (c) Whenever human skin touches the surface (i.e., the ridges of the fingerprint make contact), the light reflection is *frustrated*. That is, the light exits the prism and enters the finger, where the skin diffuses the light. Thus, little to no light reaches the camera, causing fingerprint ridges to appear dark in the image. The fact that valley locations *reflect* light whereas ridges *absorb* it produces a stark contrast, allowing such devices to capture fingerprints that are high in quality *and* contrast.

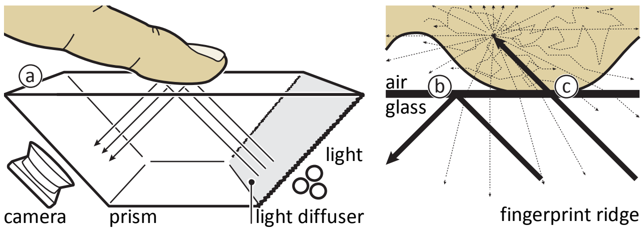

Figure 5: (a) Optical fingerprint scanners produce crisp contrast between fingerprint ridges and valleys using a prism. (b) Rays from the illuminant are totally reflected at the prism surface, causing such locations to appear *bright* as the camera sees directly into the light source. (c) Light escapes the prism (i.e., the reflection is frustrated) where fingerprint ridges touch the surface, causing ridges to appear *dark*.

Unfortunately, prism-based fingerprint scanning cannot be integrated into touch*screens*, because the prism construction does not allow these devices to produce visual output. The reason is that, as discussed above, the prism-based design requires a *specular* surface; projection, however, can only image on a *diffuse* surface.

Fingerprint scanners based on glass fibers

A number of input-only fingerprint scanners have been proposed that exploit *Fresnel reflection* inside glass fibers, a type of reflection that occurs whenever light travels from one medium to another [19], such as glass and air or glass and human skin. While the contrast between ridges and valleys is lower than in prism-based scanners [23, 20], such systems require no lens as glass fibers guide the light directly onto the sensor [23, 27].

Fingerprint scanners based on glass fibers have used slanted glass fibers and illuminate the fiber bundle from the side [10, 24] or from below [7] to produce reflections off the user's finger. Similar to prism-based scanning, light is reflected inside the fibers and guided back onto the sensor, but these reflections are frustrated once a finger touches the fibers. Other setups employ straight glass fibers, illuminate the finger through the space between the fibers, and capture the reflected light guided onto the sensor using the fibers [11]. Alternative setups use solid bundles and place them away from the camera (e.g., [17]). They illuminate the user's finger through the bundle while the camera captures all reflections. However, all such setups face the challenge of optimally illuminating the user's finger to produce light reflections that are high in contrast. While good illumination is easy to achieve for small surfaces, such as those that accommodate single fingers, their approach does not scale to larger surfaces.

While none of the previous fingerprint scanners produce *visual output* (they use glass-fiber bundles for scanning only), Fiberio offers an interactive touch*screen*.

Touchscreens based on FTIR cannot sense fingerprints

As mentioned in the introduction, touchscreens based on *frustrated total internal reflection* [13] cannot be enabled to capture fingerprints. The primary reason is that such systems employ compliant surfaces to act as diffusers and at the same time facilitate sensing touch input. Their structure is coarse, however, which dampens touch input to the extent that fingerprint ridges cannot leave distinct impressions on the waveguide. Such surfaces thus blur all the details required for fingerprint sensing.

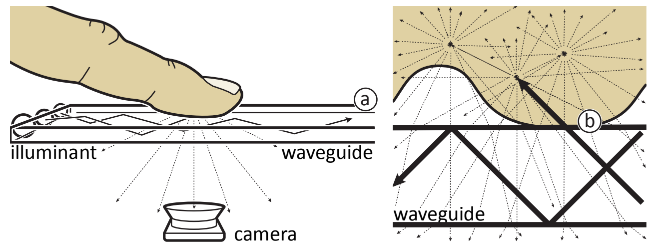

Figure 6: (a) Han's FTIR setup [13] does not afford high-contrast fingerprint scanning, even if we eliminate the compliant surface. (b) When a finger touches the surface (i.e., waveguide), fingerprint ridges frustrate the internal reflection, thus light escapes and enters the fingerprint ridges, which diffuse the light and consequently illuminate adjacent valleys. Therefore, FTIR setups illuminate the *entire* finger upon touch. Since the camera observes the entire finger and thus sees a finger that is illuminated as a whole, such system cannot resolve fingerprints with high contrast.

Even if we eliminate the light-diffusing property of the surface by removing the diffuser, the design of FTIR will still not produce the contrast required for fingerprint scanning. Figure 6 illustrates such a device without a compliant surface. When the finger touches the surface, the light escapes the waveguide and enters the ridges of the fingerprint. (b) The finger's skin, however, *diffuses the light* at a depth of 1mm, which causes the light to spill over into adjacent valleys [10, 33]. Unfortunately, the camera below the waveguide captures this diffused light for ridges and valleys alike. The finger thus appears illuminated as a whole with very little contrast between ridges and valleys.

FIBERIO'S WORKING PRINCIPLE AND OPTICAL PATH

As explained above, the key innovation behind Fiberio is that the fiber optic plate allows the screen to serve as a *diffuse* surface for projection and simultaneously act as a *reflective* surface for fingerprint scanning. We now describe the details of the optical path that enables this.

Diffuse transmission

The diffusion of projected images inside Fiberio's fiber optic plate is the result of two independent effects: (1) ring diffusion and (2) microstructural effects inside fibers.

Ring diffusion: As shown in Figure 7, light rays shone onto a fiber optic bundle with relatively large-diameter fibers (1mm) form a cone on exit. This cone manifests itself as a *ring* on a projection surface, here a table surface 5cm below the bottom surface of the fiber optic bundle.

Figure 8 explains this effect. (a) Looking into a glass fiber from one end, a light ray hits the surface of the fiber. (b) The ray enters the fiber and on its way down, the ray describes the shape of a star polygon. (c) We inject a

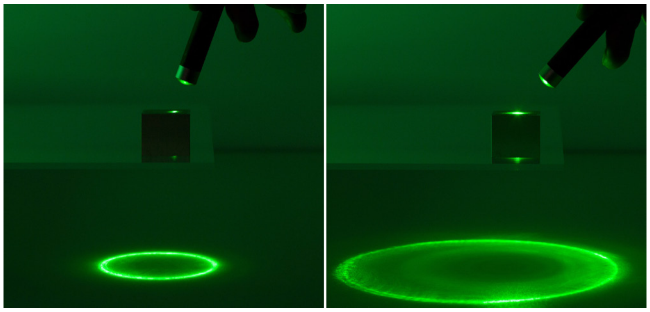

Figure 7: Pointing a laser at a fiber optic plate causes it to diffuse incident light into a ring. The angle of incident light thereby determines the radius of the ring, here small and large. The shown fiber optic bundle contains large-diameter fibers (1mm) and rests 5cm above a table surface.

second ray, parallel to the first, but at a small offset. We see how the slight offset causes the star polygon of the second ray to be made from more obtuse angles, allowing this ray to travel a greater angular distance and thus exiting in a different direction. (e) Looking at the fiber from the side, we see that the exit angle along this axis is always identical to the angle on entry. (d) With multiple rays varying by how much they "rotate" inside the fiber, but exiting at the same angle with respect to the fiber, rays form a ring.

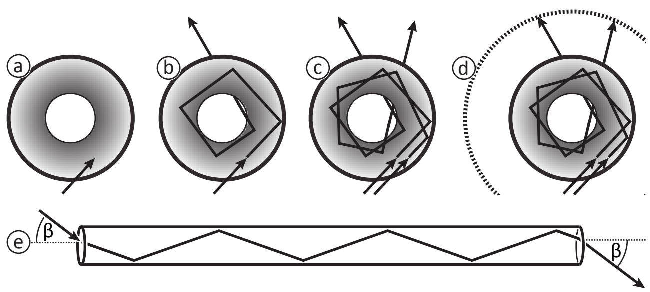

Figure 8: Each fiber diffuses parallel incident light into rings. (a) A fiber viewed top-down. (b) A ray enters the fiber and bounces down the fiber in a rotary pattern. (c) A parallel, but slightly offset ray exits into a different azimuth direction. (d) This variation in azimuth causes a ring, because (e) all rays have a constant exit angle with respect to the fiber.

Microstructural effects inside fibers: In contrast to the large-diameter fibers, a fiber optic plate made from very small-diameter fibers produces not only ring diffusion, but also much more diffuse light scattering as shown in Figure 9. This is essential for making Fiberio's projected image visible from all sides. At 6µm, each fiber in our fiber optic plate is only an order of magnitude larger than the wavelength of the light it transports, causing transmitted rays to scatter due to diffraction effects. In addition, the light reflected inside the fibers is subject to the microstructure of each fiber's core and cladding [19], which produces variations in reflection angles inside each fiber. Due to the thinness of such fibers, light is frequently reflected inside the fibers, which causes microstructural effects to manifest themselves in a stronger scattering of light upon exit.

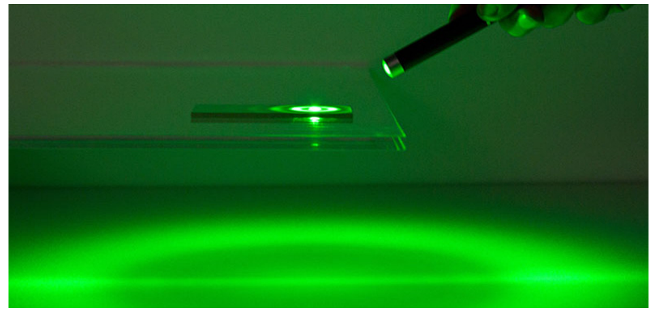

Figure 9: A fiber plate with a multitude of very small-diameter fibers (6µm) blurs ring diffusion, which scatters the incoming light into all directions. This is the basis for good light diffusion, which we need to produce an image on a touchscreen. The fiber plate rests 5cm above the table. The image on the plate is visible even from extreme angles.

As shown in Figure 9, the light diffusion produced by the fiber optic plate exhibits a mild hotspot around the ring. We account for this in Fiberio's setup by mounting the projector at an angle with respect to the fiber optic plate to further increase the amount of light diffusion.

In summary, the fiber optic plate diffuses light while *conducting it along* the fiber; this is different from the traditional way of diffusing light while passing through a diffuse *surface*. Diffusing light while conducting it allows Fiberio to maintain a specular surface, which is key to generating the contrast required for fingerprint capturing.

Sensing fingerprints using frustrated reflections

The specular reflection of light at the *top* surface of the fiber optic plate is what allows Fiberio to capture fingerprints. These reflections occur when the light *exits* fibers.

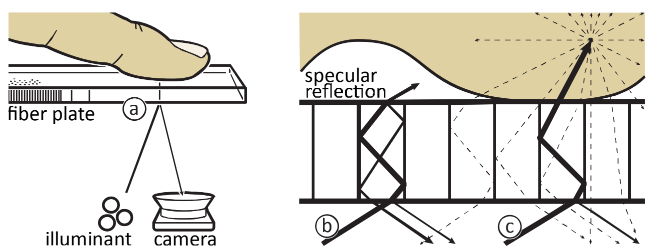

Figure 10: (a) The illuminant shines light onto the fiber optic plate. (b) A portion of the incoming light is reflected at the top of the fiber, traveling back down the fiber, where the camera observes it. (c) A fingerprint ridge touching the fiber, in contrast, frustrates the reflection at the top end of the fiber, so that only little light travels back down the fiber, causing this spot to appear dark to the camera.

As illustrated by Figure 10a, Fiberio shines infrared light onto the fiber optic plate from below. Some light is reflected at the bottom surface, but most light enters and travels up the fibers (Figure 10b). A large portion of the light exits the fibers, but the remaining portion is reflected at the top surface; the reflected light then travels back down inside the fibers and exits at the bottom, where Fiberio's camera observes it. Due to the reflection at the top surface of the plate, locations of fingerprint valleys and areas around the finger appear "brighter" in the resulting image.

If, however, a fingerprint ridge makes contact with the top end of the fiber (Figure 10c), the reflection at the top surface is frustrated and *almost all* light exits the glass fibers. Only a negligible fraction of light travels back down the fiber, so that this point appears "dark" to the camera.

The contrast between the light reflected at the top surface and the frustrated reflection allows Fiberio to sense fingerprints. Compared to prism-based scanning, this mechanism offers less contrast, because it returns only a small percentage of light. Since we use a camera with very low noise, however, we obtain a good signal-to-noise ratio. Fiberio thus extracts high-quality fingerprints from the captured images with fingerprint edges that appear very sharp.

In the optimal case, all light reflections are frustrated at the top surface when a fingerprint ridge is in contact. However, this requires that the skin of the finger be in direct contact with the fibers. In the case of a very dry finger (or dust on the skin), the frustrations may fail to occur at some locations, causing only a partial fingerprint to appear.

To address this, we created a thin compliant surface by pouring a layer of silicone onto the fiber plate. After having cured, the silicone increased the quality of the fingerprint. At the same time, it reduced the polished impression upon touch, which impeded dragging to a small extent.

In practice, we found no compliant layer to be necessary even for dry fingers, because over time the user's fingers leave small amounts of remnant grease on the surface. This facilitates the process of light coupling into dry skin without affecting the quality of projection or fingerprint sensing.

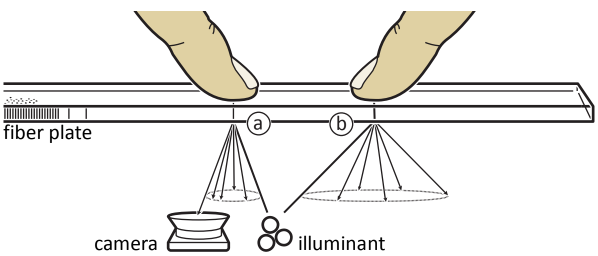

Figure 11: The light that comes back down the fiber is subject to same ring diffusion that we described earlier in terms of projection. While the camera will see reflections off the fiber plate's surface at location (a), reflections from location (b) will be invisible, because the camera does not sit on the same ring.

Placing the illuminant and camera for optimal contrast

We explained in the previous sections how the fiber optic plate enables scanning fingerprints at particular locations; to enable fingerprint scanning across the entire large surface of Fiberio, the location of camera and illuminant become important. The illuminant needs to shine light at the entire screen from below while the camera has to be placed so as to capture the reflected light coming back down the fibers.

Figure 11 illustrates the challenge. The light that comes back down the fiber is subject to same ring diffusion that we described earlier in the context of projection. To enable the camera to capture reflections across the entire surface, we need to place the camera so that it is in the optical path of the returning light. We explored three solutions.

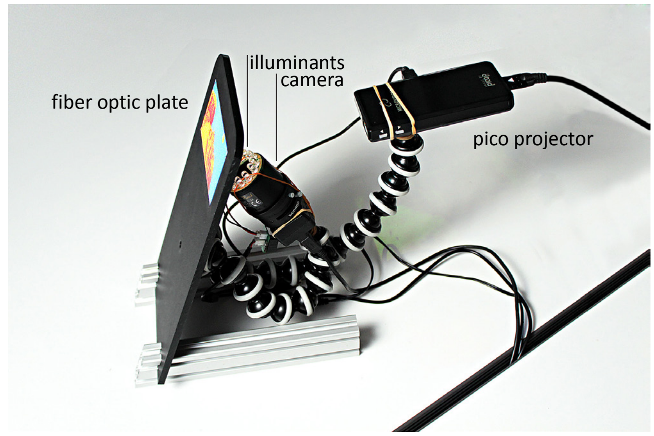

Figure 12: This earlier prototype placed the illuminant *around* the camera to approximate a shared location of camera and light source. Camera and illuminant were tilted with respect to the screen to prevent the camera from seeing the reflection of the illuminant in the fiber optic plate (hotspot).

Solution 1: Shared location for camera and small illuminant

Our first solution was to place the illuminant in the same location as the camera—or *around* the camera to approximate a shared location of camera and light source (Figure 12). This arrangement causes light to ring-diffuse back into the camera for *all* locations on the screen as shown in Figure 13. In the shown design, we offset both camera and illuminant from the screen and mounted them at an angle in order to prevent the camera from seeing the direct reflections of the illuminant (i.e., hotspots).

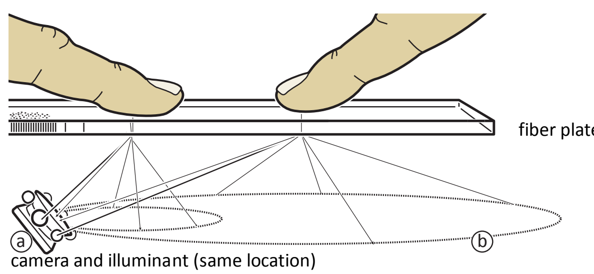

Figure 13: (a) Placing camera and illuminant in the same location causes the returning, ring-diffused light to always hit the camera. The farther away the finger, however, the less intense such reflections appear as they spread along increasingly large rings (b).

While this design works well on a small prototype, it does not scale to large screens. In this case, the intensity of the reflected light falls off with increasing distance to touch contacts as shown in Figure 13b. Eventually, the sensor in the camera will not be sensitive to resolve the contrast between fingerprint ridges and valleys for far-away touches, causing the resulting fingerprints to appear noisy. Since we scaled Fiberio to its current 19″ size, we switched to designs that illuminate the screen using a large homogenous illuminant.

Solution 2: Using a large homogenous illuminant

Our current Fiberio prototype uses evenly distributed illumination across the entire surface. The illuminant uniformly shoots light at the fiber optic plate from below, creating one evenly illuminated area. Since light intensities are roughly identical across the entire surface, no single hotspot occurs and thus no area of oversaturation or undersaturation in the camera image.

As shown in Figure 14, we prototyped two approaches to create a light source that evenly illuminates the fiber plate. In an earlier prototype, we placed a uniform area illuminant below the fiber optic plate (here Acrylight LED [8]) as shown in Figure 14a. The main limitation of this solution was that it produced low contrast, as the reflected light from the fingerprint not only competes with light reflected directly off the bottom of the fiber optic plate, but the illumination layer also shines light directly into the camera. We addressed this with yet another iteration on our design.

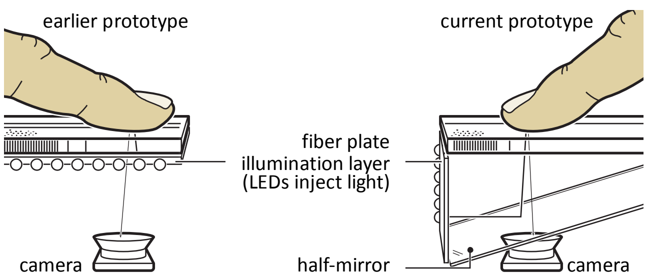

Figure 14: Fiberio evenly illuminates the entire surface, creating one even reflection to see fingerprints across the whole surface. (left) An earlier prototype used Acrylite LED below the fiber plate. (right) Our current prototype uses a half-mirror that reflects illuminations from the side.

Current solution: even illumination via a half-mirror

Figure 14b illustrates the conceptual setup that we use in our current prototype as shown in Figure 15. It continues to use Acrylite LED to illuminate a large area. However, we now place the sheet at the side of the table and use a half-silvered mirror to reflect illumination to the fiber optic plate. This prevents the camera from seeing the illuminant layer directly and thus avoids the loss of contrast that characterized our earlier design.

The resulting design works well and since this setup illuminates the screen using a large illuminant, the solution scales well to large screens, even beyond the 19″ of our current Fiberio prototype.

DETAILS ON HARDWARE SETUP

As shown in Figure 2, Fiberio offers a 40cm×25cm screen surface (16″×10″, 19″ diagonal). This surface we implement by tiling two 25cm×20cm fiber optic plates (Incom B7D59-6), which are polished and feel like a piece of glass.

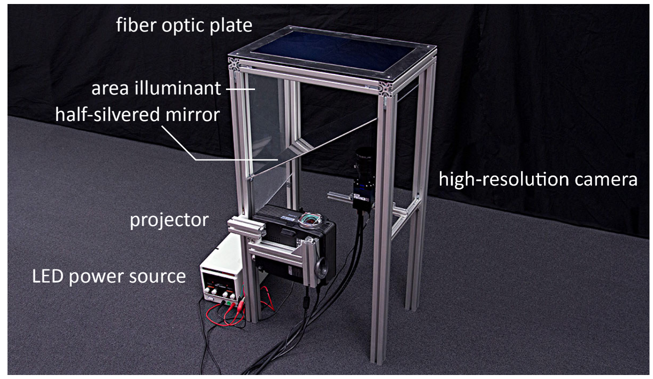

Figure 15: Our current prototype illuminates the fiber optic plate evenly, creating optimal reflections for the camera to resolve fingerprints at all locations on the touch surface. We use an area illuminant (Acrylite LED with light injected from the sides) mounted to the side of the table and a half-silvered mirror to reflect illuminations. All sides of the table are normally covered with black cloth to prevent reflections from the environment in the camera image (here we left out the covers to show the inner components of the system).

The BenQ short-throw projector pointed at the screen offers a resolution of 1024×768px. A hot mirror in front of the projector prevents interference with the cameras. Due to its high resolution, the fiber optic plate has no impact on the resolution of the projected image; each fiber measures 6 microns, whereas a projected pixel measures ~390 microns and thus covers a multitude of fibers. Projected images are visible even from extreme angles (Figure 9), because of the numerical aperture of the fibers we use (1.0). The refractive index of their core (1.8) and that of the cladding (1.49) allows for maximum acceptance and exit angles of 90°.

A frame made from a 40mm aluminum profile system holds Fiberio's components in place. Fiberio's height of 38″ is designed to minimize fatigue on the standing workstation.

To achieve fingerprint scanning across Fiberio's entire surface at a resolution needed for reliable scanning (500dpi [20]), our setup would require a camera resolution of 8000×5000 pixels. In our prototype, we used a high-resolution camera (Teledyne Dalsa Falcon2, 4000×3000px, 60fps, 6ms shutter speed), which observes only a sub region of Fiberio's surface (20cm×15cm). We supplemented this approach with a web camera to enable touch interaction across the entire surface (Sony PS3, 640×480px, 75fps), which we set up in a diffused illumination arrangement. Both cameras and the projector are calibrated to a shared world-coordinate system.

While our prototype setup using a half-mirror achieves the best illumination across Fiberio's whole surface, the switch to scanning prints on only a quarter of the surface allowed us to reduce the footprint of the table. We therefore substituted the half-mirror with one 4W infrared illuminant.

IMAGE PROCESSING

Currently, Fiberio locates and tracks all touches based on the low-resolution camera, implementing a typical diffused illumination processing pipeline [22]. When touches enter the region observed by the high-resolution camera, Fiberio locates fingerprints, extracts them along with their features, and matches features against the records stored in its fingerprint database.

Future versions of Fiberio will cover the entire screen either using a 2×2 array of high-resolution cameras or using a single camera and a high-speed pan and tilt mirror.

Fingerprint processing pipeline

To extract the locations and directions of fingerprint features, i.e., ridge endings and bifurcations (so-called *minutiae*), which allow identifying users, we implemented the algorithms commonly used to process fingerprints [20]. Figure 16 illustrates our pipeline.

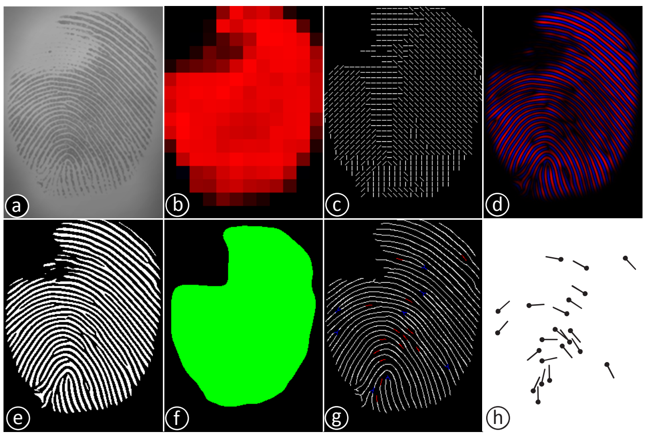

Figure 16: Fingerprint processing pipeline (images are cropped). (a) Raw image, (b) areas of high standard deviation, (c) flow field, (d) Gabor filter, (e) binarized fingerprint, (f) mask, (g) skeleton and (h) extracted locations and orientations of all fingerprint features.

The 768×768 pixel raw image shown in Figure 16a contains the reflections from the user's finger. Fingerprint ridges appear as dark lines inside a brighter area. Fiberio starts by removing possible luminance gradients by subtracting a low-pass copy from the image. (b) Fiberio locates fingerprints by calculating the standard deviation of brightness values for 16×16-pixel subregions in the image. High brightness deviation indicates the presence of adjacent ridges and valleys. Fiberio uses this to produce a mask—all further processing takes place inside this area.

To improve the contrast of the fingerprint, (c) Fiberio computes the direction of the main gradient across all 8×8-pixel subregions, resulting in the flow field of the fingerprint. We input the flow field into (d) a Gabor filter, which improves the edges in the fingerprint according to their orientation, thereby smoothing noisy and interrupted ridges. (e) Binarizing the result now brings out a sharp contrast between ridges and valleys in the fingerprint.

To extract the locations of all minutiae from the fingerprint, Fiberio obtains (f) a refined mask of the fingerprint and (g) derives the skeleton of the binarized fingerprint. The skeleton reveals the locations and orientations of minutiae; locations in the skeleton that have three neighboring pixels are bifurcations, whereas locations with only one neighbor are ridge endings as shown in Figure 16h.

To match two fingerprints based on their minutiae, Fiberio finds the best spatial alignment of both point sets using Bozorth matching [20]. It then computes a matching score based on the number of minutiae that match in terms of location and angle. When Fiberio compares an observed fingerprint to fingerprints in its database, it requires fingerprints to match in at least 10 minutiae locations.

GPU acceleration and resulting performance

Fiberio runs touch recognition, fingerprint extraction, matching, and graphics using parallel threads, allowing it to stays responsive to user input at all times. Since processing fingerprints is computationally expensive, we implemented our pipeline in CUDA 4.2 to run on the GPU (NVidia GTX 680), which allows our system to run at interactive rates.

Extracting all minutiae from the raw fingerprint image currently takes Fiberio 21ms per frame. We expect this to get even faster with newer graphics cards. The speed of matching fingerprints currently increases linearly with the number of records in the database (0.55ms per record).

EVALUATION

The purpose of our evaluation was to verify that Fiberio's sensor setup captures fingerprints with sufficient quality to allow it to recognize users reliably. To evaluate identification performance, we compared 30 fingers (three fingers per each of the 10 participants, ages 20–32, 2 female).

Apparatus: We conducted this evaluation using an earlier version of our prototype, which featured a lower-resolution camera (8.8MP Flea3). Considering that the image sensor of that camera was inferior to that of our current camera and we used our current algorithms for processing input, the results from this evaluation apply to our current prototype. The study apparatus was set up to capture fingerprint images at a resolution of 500dpi and 8ms shutter time. We performed all processing on a 2.2 GHz Intel Core2 Duo processor with 4 GB of RAM and an NVidia GTX 680 graphics card using the described algorithm. The projector was switched off.

Task and procedure: As shown in Figure 17, participants touched the screen region captured by the high-resolution camera during each trial, each time using one of their right hand's index, middle or ring finger. Participants thereby used their finger pad for touch input and repeated input five times, performing fifteen trials overall. Due to the limited frame rate of the camera we used during the evaluation, participants were required to hold a touch for around 400ms. This allowed the camera to capture frames reliably. This is no longer required for our current system due to the substantially larger frame rate of our current camera. For each trial in the evaluation, Fiberio processed only a single frame, namely the one in which the area of the touch

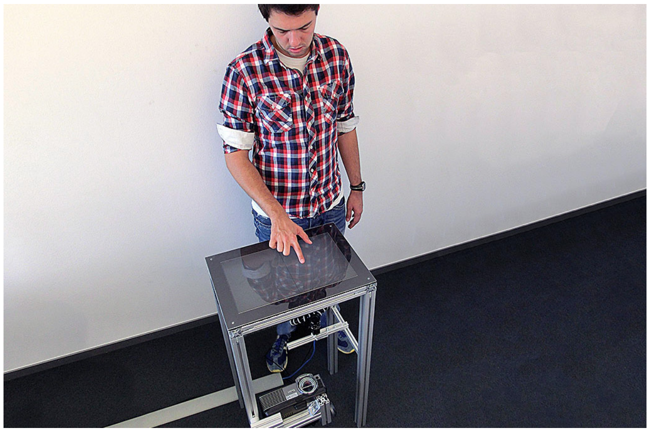

Figure 17: A study participant during the evaluation. The prototype was configured to provide no feedback.

contact was maximal across the entire event. Participants received no feedback during the evaluation.

Processing: The evaluation resulted in 150 captured fingerprints, from which we extracted the minutiae sets and created a database. We then performed minutiae-based matching on each of the captured prints against all 149 other records.

Results and Discussion: The cross-validated analysis resulted in 148 of 150 fingerprints being *correctly* matched, 0 *wrong* matches, and 2 *no matches* (i.e., samples that produced less than the minimum number of 10 minutiae needed for identification). The average processing time for matching a minutiae set against all others was 267ms.

These findings show that Fiberio identifies users reliably by their fingerprints and at interactive rates. Since the speed of user identification scales linearly with the number of samples in the database, this process runs asynchronously to still support responsive interaction.

Of course, participants used their finger pads when providing input, which allowed for optimal feature extraction. While flat fingers exhibit more than 100 minutiae, fingertips contain fewer features ($0.18/mm^2$ [34]). However, 12-15 visible features suffice to identify users when touching, which fingertips may provide depending on their tilt. Fiberio's height of 38″ facilitates touching with flat finger angles, which is optimal to extract a multitude of features. While users might be less careful during regular use, a live system could produce feedback on their touch events and ask for repeated input upon unsuccessful identification.

Note that a lack of visible features in a touch does not lead Fiberio to misidentify users. If a fingerprint exhibits too few features, Fiberio does not attempt to identify users.

CONCLUSIONS

In this paper, we presented Fiberio, a touchscreen that senses fingerprints. The key to making this possible is the fiber optic plate, which offers both specular reflection and diffuse transmission.

While our key contribution certainly is a touchscreen that performs user identification and secure authentication during interaction, Fiberio also implements a standard diffused illumination table. This results in additional desirable properties, such as the ability to recognize fiducial markers and detect objects that hover above the surface, such as the user's fingers and hands as shown in Figure 18. On the flip side, similar to other diffused illumination setups, Fiberio's rear projection requires space and it is susceptible to interference by strong infrared light sources in the environment.

A positive side effect of the fiber optic plate is that Fiberio is inherently free of parallax. Users see the projected output *on top* of Fiberio's screen; when users touch that output, Fiberio's cameras see this touch contacts exactly where it occurs, because touch contacts appear at the bottom surface of the fiber optic plate. Combined, this allows for particularly precise input.

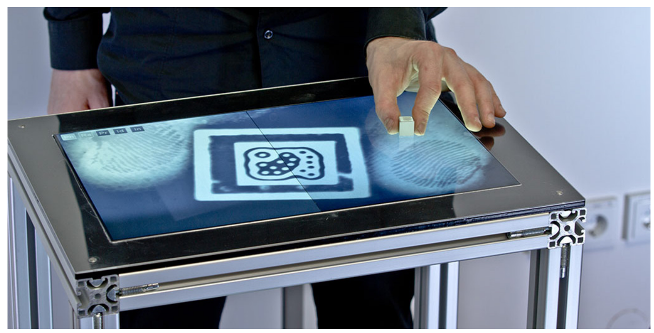

Figure 18: Fiberio recognizes touch, but also hovering objects (here fingers) as well as fiducial markers. The fiducial marker on this tangible object measures only 3mm×3mm.

Finally, Fiberio is subject to the same limitations as other biometric authentication mechanisms, such as the risk of spoofing using fake fingerprints [20], as well as concerns in terms of surveillance and respecting users' privacy. To evaluate Fiberio's capabilities in identifying users amongst a large population, a deeper evaluation of the system with a large number of participants of a large span of ages and a wider range of demographics.

In summary, Fiberio opens up a lot of new possibilities for interactive systems. For fifteen years, researchers have hypothesized the existence of a touchscreen with biometric authentication, be it for activity logging [6], high degree-of-freedom touch input [32], and high-precision touch input [15] by modeling touch as a 3D input operation [16]. These are all possible now based on the principles of Fiberio and our future work includes implementing such use-cases on our prototype. While Fiberio's current configuration does not translate to mobile devices, we plan on exploring flat form factors using in-cell technology [5] or integrating a wedge that folds the optical path as part of future work.

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