Low-Cost Multi-Touch Sensing through Frustrated Total Internal Reflection

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Figure 1: Simple examples of multi-touch interaction using our FTIR technique

ABSTRACT
This paper describes a simple, inexpensive, and scalable technique for enabling high-resolution multi-touch sensing on rear-projected interactive surfaces based on *frustrated total internal reflection.* We review previous applications of this phenomenon to sensing, provide implementation details, discuss results from our initial prototype, and outline future directions.

ACM Classification: H.5.2 [**User Interfaces**]: Input Devices and Strategies

General Terms: Human Factors

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INTRODUCTION

While touch sensing is commonplace for single points of contact, it is still difficult and/or expensive to construct a touch sensor that can register *multiple* simultaneous points of contact. Multi-touch sensing enables a user to interact with a system with more than one finger at a time, as in chording and bi-manual operations. Such sensing devices are inherently also able to accommodate *multiple users* simultaneously, which is especially useful for larger shared-display systems such as interactive walls and tabletops. Initial investigations, though sparse due to the prohibitive availability of these devices, nonetheless reveal exciting potential for novel interaction techniques [1][2][11][12][19][23][26][27].

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We present a simple technique for robust multi-touch sensing at a minimum of engineering effort and expense. It is based on *frustrated total internal reflection (FTIR)*, a phenomenon familiar to both the biometric and robot sensing communities. It acquires true touch image information at high spatial and temporal resolutions, is scalable to large installations, and is well suited for use with rear-projection. It is not the aim of this paper to explore the multi-touch interaction techniques that this system enables, but rather to make the technology readily available to those who wish to do so.

RELATED WORK

A straightforward approach to multi-touch sensing is to simply utilize a plurality of discrete sensors, making an individual connection to each sensor as in the *Tactex MTC Express* [20]. They can also be arranged in a matrix configuration with some active element (e.g. diode, transistor) at each node, as in the device featured in Lee et al.'s seminal work [11], and also in Westerman and Elias's commercial *FingerWorks iGesturePad* [3][22].

Through careful driving techniques, it is possible to gather multi-touch information from a purely passive matrix of force-sensitive-resistors (FSRs) as developed by Hillis [6], or capacitive electrodes, such as in [18] and the recent *SmartSkin* [19], and thus achieve a great reduction in complexity. However, these devices still require very many connections, which keeps their resolution limited in practice (under 100×100). Furthermore, these systems are visually opaque, forcing systems to resort to top-projection for integration with a graphic display.

Alternatively, video cameras present a very convenient way to acquire high-resolution datasets at rapid rates, and thus have naturally been explored for touch sensing. Recent approaches include estimating depth from intensity as in *HoloWall* [15], estimating depth from stereo as in *TouchLight* [26] and the *Visual Touchpad* [12], and tracking markers embedded within a deformable substrate as in *GelForce* [8].

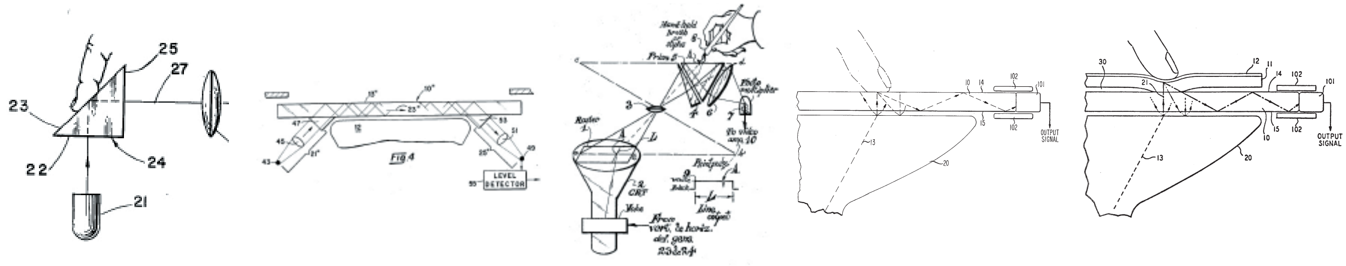

Figure 2: Some previous applications of FTIR to sensing:
disclosures by (a) White; (b) Johnson and Fryberger; (c) Mueller; (d) Mallos; (e) Kasday

FTIR SENSING TECHNIQUES

An interesting group of techniques are those that make use of *frustrated total internal reflection (FTIR)*. When light encounters an interface to a medium with a lower index of refraction (e.g. glass to air), the light becomes refracted to an extent which depends on its angle of incidence, and beyond a certain *critical* angle, it undergoes total internal reflection (TIR). Fiber optics, light pipes, and other optical waveguides rely on this phenomenon to transport light efficiently with very little loss. However, another material at the interface can *frustrate* this total internal reflection, causing light to escape the waveguide there instead.

This phenomenon is well known and has been used in the biometrics community to image fingerprint ridges since at least the 1960s [25]. The first application to touch input appears to have been disclosed in 1970 in a binary device that detects the attenuation of light through a platen waveguide caused by a finger in contact [7].

Mueller exploited the phenomenon in 1973 for an imaging touch sensor that allowed users to "paint" onto a display using free-form objects, such as brushes, styli and fingers [17]. In that device, light from the flying spot of a CRT is totally internally reflected off the face of a large prism and focused onto a single photodetector, thereby generating an updating bitmap of areas that are being contacted. Greene rediscovered this method in 1985 in his *Drawing Prism* [5], but updated in optically inverted configuration, with a video camera and a broad light source replacing the CRT and photodetector.

Mallos disclosed a CRT-based touch sensor in 1981 which replaces the bulky prism with a thin platen waveguide [13], and operates by detecting the light *scattered* away by an object in optical contact. Some more recent fingerprint sensors take this approach as well [4].

The robotics community has also used this approach since 1984 in the construction of *tactile sensors* for robot grippers, but with a *compliant surface overlay* [27][16][23]. This is a structured flexible membrane which is normally kept separate by an air-gap, but when depressed, makes optical contact with the waveguide. This effectively makes the sensor responsive to force rather than contact. Kasday proposes a similar modification [9] to the Mallos sensor.

IMPLEMENTATION

Though these FTIR techniques have fallen out of usage, modern-day accessibility to machine vision hardware and processing makes a compelling case to revisit them. For multi-touch sensing, we adapt the Mallos/Kasday design, but in its *dual* configuration, with the optical paths reversed. Alternatively, it can be thought of as a FTIR fingerprint sensor, or a FTIR robot tactile sensor, only greatly scaled up.

In our prototype, we use a 16"x12" (406mm x 305mm), ¼" (6.4mm) thick sheet of acrylic, whose edges have been polished clear, as an optical waveguide. Common glass is unsuitable here due to its poor optical transmittance; however we have also used clearer glass formulations (e.g. "water white") successfully. Though more expensive, such glass is structurally stiffer, and is far less easily scratched than acrylic.

This sheet is *edge-lit* by high-power infrared LEDs, which are placed directly against the polished edges so as maximize coupling into total internal reflection (total optical power: 460mW @ 880nm), while a digital video camera equipped with a matching band-pass filter is mounted orthogonally. TIR keeps the light trapped within the sheet, except at points where it is frustrated by some object (e.g. finger) in optical contact, causing light to scatter out through the sheet towards the camera (see Figure 3).

Only simple image processing operations (rectification, background subtraction, noise removal, and connected components analysis) are required for each frame, while routine machine vision tracking techniques are used to interpret the sequences into discrete touch events and strokes. Video is captured at 8-bit monochrome at 30fps at a resolution of 640x480 (corresponding to $1mm^2$ precision on the surface); all processing is easily performed in real-time by a modest 2GHz Pentium 4 workstation.

Our technique provides full imaging touch information without occlusion or ambiguity issues. The touch sense is zero-force and true: it accurately discriminates touch from a very slight hover. It samples at both high temporal and spatial resolutions. Pressure is not sensed, though this is largely mitigated by the precision with which it can determine the contact area of a depressed finger. It is inexpensive to construct, and trivially scalable to much larger surfaces- the only considerations one needs to make in constructing a wall-sized touch display, are camera resolution, and the amount of illumination necessary to cover the area. The surface also need not be planar, providing for some interesting design flexibility.

A drawback of the approach is that, being camera-based, it requires a significant amount of space behind the interaction surface, though we primarily expect application scenarios where rear-projection would have been employed anyway (e.g. interactive walls, tables). Also, as an optical system, it remains susceptible to harsh lighting environments.

Combining with Rear-Projection Display

This sensor can be used standalone, but because it is completely visually transparent, it is particularly suited for use in combination with rear-projection, without a loss in brightness. We place a diffuser on the rear (non-interaction) side of the waveguide, which does not frustrate TIR because a tiny air-gap exists between the two. The diffuser also does not appreciably affect the IR image needed to be seen by the camera, since it is very close to the light sources (e.g. fingers) being imaged.

This scheme does introduce a disparity between the display and interaction surfaces, corresponding to the thickness of the waveguide (¼” in our prototype), but there is no functional reason, other than ease of implementation, that the waveguide cannot be made thinner. Rigidity becomes a concern at larger dimensions, at which point another layer of transparent material can be stacked to the rear to add structural support without adding further disparity.

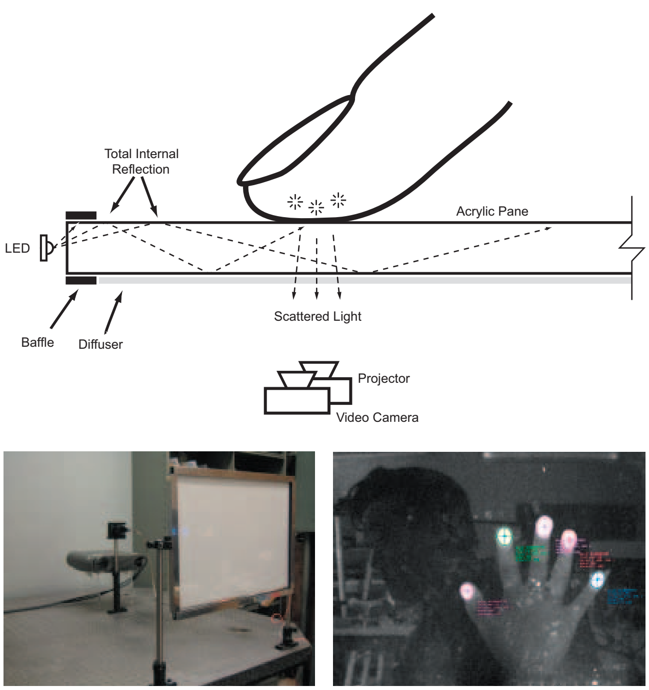

Figure 3: Schematic overview (top);
Prototype setup (left); Video output w/o diffuser (right)

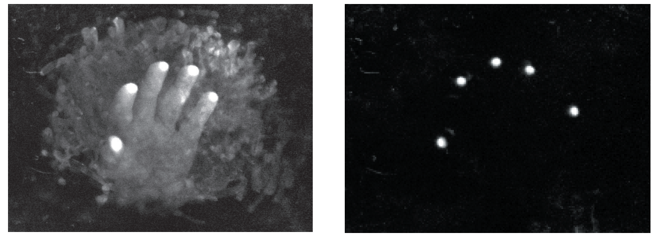

Figure 4: Output from contaminated surface (left), and when using a compliant surface overlay (right)

Robustness

The response of the sensor is highly dependant on the optical qualities of the object being sensed; while this is beneficial in many ways (e.g. it won’t falsely register a mug lying the surface), it also means that the device may not detect gloved hands or arbitrary styli. Notably, dry skin generates a weaker optical signal, though in our experience the user can press harder against the sensor to compensate (though this does impair movement and fatigues the user).

Over extended usage, the surface can become contaminated with oils and sweat left behind from users, along with nicks and scratches, creating an increase in background noise against which a true signal must be isolated (see Figure 4). Over the short term, this is compensated for by the video processing system with an adaptive background model. However, over the long term, as dry skin performance starts to suffer, the surface eventually must be cleaned. Alternatively, multiple infrared wavelengths could be used to better discriminate a live finger from latent residues.

Using a Compliant Surface

As in prior work, we can stabilize performance with the use of a compliant surface overlay. We have tested a variety of plastic films and sheeting that are readily available, and have found, remarkably, that common vinyl rear-projection screen material, such as “Rosco Gray #02105”, is itself a reasonable overlay for HCI applications. By making the display screen itself the interaction surface, we also conveniently eliminate any disparity between the two.

With the overlay, the sensor no longer responds binarally to optical contact, but to a range of *force*, expressed as pixel intensity. However, because an actual deformation occurs within the membrane when depressed, there is hysteresis in the response, especially upon relaxation. In our tests with the projection screen material, it can take up to a full second for an excessively forced depression to completely dissipate. Nevertheless, its performance under normal HCI usage is quite satisfactory. We feel that improving performance here is merely a matter of discovering/engineering a material that has suitable stiffness, resiliency, textural, and scattering properties for this application, and we shall continue to search for low-cost solutions to this.

FUTURE WORK

We consider the greatest drawback to our approach to be how little other information it provides about the tactile image. The system provides no proximity (i.e. “hover”) information, nor any ability to label or classify each point of contact. It is unable to determine, for example, whether two contacts were produced by fingers from the same hand, or from two distinct hands, or from two distinct users. Our intention is to attempt several approaches to “see through the screen” while utilizing the FTIR technique, leading to an elegantly unified touch/gesture system.

One approach will be to work with exotic screen materials such as the holographic film employed by *TouchLight* [26]. We have been experimenting with the less expensive, directionally scattering film used recently in the *Lumisight Table* [14]. It is also conceivable that a Rayleigh-scattering material can be found that diffuses visible wavelengths, but is substantially transparent to a convenient infrared band. We may also try an electroswitchable screen, which can rapidly alternate between a transparent and a translucent state under electronic control, as used in the *blue-c* system [10].

Alternatively, we have discovered that typical LCD display panels do not significantly affect infrared light, and so we have been experimenting with relocating the backlight, and placing an IR camera directly behind such a panel. This approach also carries with it the benefits of reduced volume and increased portability.

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