Printed Optics: 3D Printing of Embedded Optical Elements for Interactive Devices

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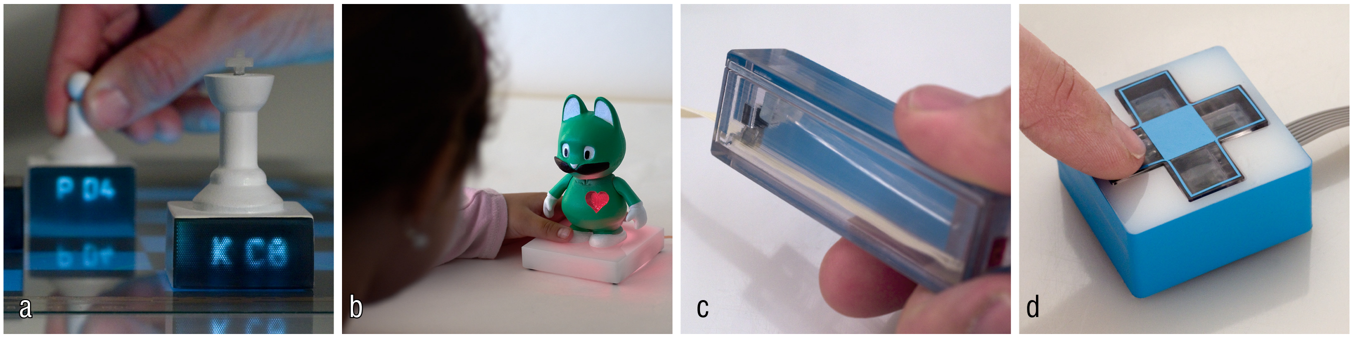

Figure 1: Custom optical elements are fabricated with 3D printing and embedded in interactive devices, opening up new possibilities for interaction including: unique display surfaces made from 3D printed 'light pipes' (a), novel internal illumination techniques (b), custom optical sensors (c), and embedded optoelectronics (d).

ABSTRACT

We present an approach to 3D printing custom optical elements for interactive devices labelled *Printed Optics*. *Printed Optics* enable sensing, display, and illumination elements to be directly embedded in the casing or mechanical structure of an interactive device. Using these elements, unique display surfaces, novel illumination techniques, custom optical sensors, and embedded optoelectronic components can be digitally fabricated for rapid, high fidelity, highly customized interactive devices. *Printed Optics* is part of our long term vision for interactive devices that are 3D printed in their entirety. In this paper we explore the possibilities for this vision afforded by fabrication of custom optical elements using today's 3D printing technology.

ACM Classification: H.5.2 [Information Interfaces and Presentation]: User Interfaces.

Keywords: 3D printing; optics; light; sensing; projection; display; rapid prototyping; additive manufacturing.

INTRODUCTION

3D printing is becoming increasingly capable and affordable. We envision a future world where interactive devices can be printed rather than assembled; a world where a device with active components is created as a single object, rather than a case enclosing circuit boards and individually assembled parts (Figure 2). This capability has tremendous potential for rapid high fidelity prototyping, and eventually for production of customized devices tailored to individual needs and/or specific tasks. With these capabilities we envision it will be possible to design highly functional devices in a digital editor — importing components from a library of interactive elements, positioning and customizing them, then pushing 'print' to have them realized in physical form. In this paper we explore some of the possibilities for this vision afforded by today's 3D printing technology. Specifically, we describe an approach for using 3D printed optical elements, *Printed Optics*, as one category of components within a greater library of reusable interactive elements.

Custom optical elements have traditionally been expensive and impractical to produce due to the manufacturing precision and finishing required. Recent developments in 3D printing technology have enabled the fabrication of high resolution transparent plastics with similar optical properties to plexiglas^{TM}. One-off 3D printed optical elements can be designed and fabricated literally within minutes for significantly less cost than conventional manufacturing; greatly increasing accessibility and reducing end-to-end prototyping time. 3D printed optical elements also afford new optical form-factors that were not previously possible, such as fab-

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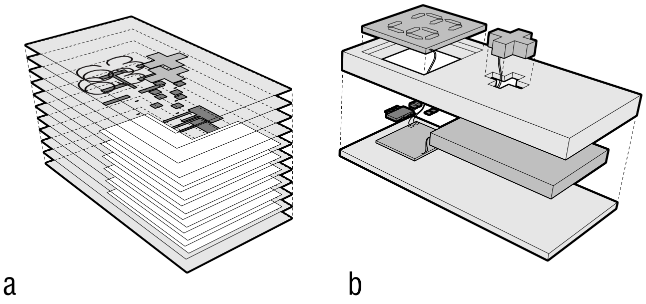

Figure 2: We envision future interactive devices that are 3D printed from individual layers (a) rather than assembled from individual parts (b). These devices will be fabricated from multiple materials to form active functional components within a single 3D print.

ricating structures within other structures, printing multiple materials within a single optical element, and combining mechanical and optical structures in the same design.

Printed Optics opens up new possibilities for interaction. Display surfaces can be created on arbitrary shaped objects using 3D printed 'light pipes' (Figure 1a). Novel illumination techniques allow the internal space within a 3D printed object to be used for illumination and display purposes (Figure 1b). Custom optical sensors can be 3D printed with the structure of interactive devices to sense user input (Figure 1c). Optoelectronic components can be completely enclosed inside optical elements to produce highly customizable and robust interactive devices (Figure 1d).

Our long term vision to digitally fabricate high fidelity, highly customized, 'ready-to-go' devices will be a powerful enabling technology for HCI research. Although much of this novel technology is still in the research stage [7, 26, 33], the simplest forms of 3D printing are rapidly entering the mainstream. A recent cover story in *The Economist* suggests 3D printing is *the* manufacturing technology to "change the world" [32]. A host of consumer-level 3D printing devices are now available and the fundamental photopolymer printing technology behind *Printed Optics* has been demonstrated for less than $200 parts cost [21]. It is reasonable to expect that inexpensive optical 3D printers will be available to researchers in the very near future.

Using today's 3D printing technology we aim to demonstrate that the design of optical systems for interactive devices can be greatly enhanced. We present the following contributions:

1. A general approach for using 3D printed optical elements, *Printed Optics*, embedded in interactive devices to display information and sense user input.
2. Techniques for displaying information using 3D printed optical elements, including the use of 3D printed 'light pipes' and internal air pockets.
3. Techniques for sensing user input with 3D printed optical elements, including touch input with embedded sensors, mechanical displacement of 3D printed light guides, and movement sensed along 3D printed mask patterns.
4. Example applications that demonstrate how *Printed Optics* can be implemented and used in interactive devices.

In the remainder of this paper we introduce the technology that enables us to create *Printed Optics* and outline the fabrication process and its capabilities. We then describe four categories of fabrication techniques for *Printed Optics*: Light Pipes, Internal Illumination, Sensing Mechanical Movement, and Embedded Components. We conclude with discussion of limitations and future research directions. With the continuing emergence of 3D printing technology, we believe now is an ideal time to explore the unique capabilities of 3D printed optical elements for interactive devices.

PRINTED OPTICS

3D printing allows digital geometry to be rapidly fabricated into physical form with micron accuracy. Usable optical elements can be designed and simulated in software, then 3D printed from transparent material with surprising ease and affordability. In this section of the paper we describe the fabrication process for 3D printing optical elements and discuss the unique capabilities that this technology enables.

Fabrication

The fabrication process begins with a digital geometric model that is converted into a series of slices to be physically fabricated layer-by-layer. 3D printing of optical quality materials typically requires a photopolymer-based process. Each layer is fabricated in sequence by selectively exposing a liquid photopolymer material to an ultra-violet (UV) light source, causing the material to cure into a solid state. Traditionally this has been achieved using 'stereolithography', where a precise laser is traced through a vat of liquid photopolymer. Other approaches include controlled exposure to UV light using a projector, or physical deposition of liquid photopolymer in the presence of a UV light source. The fundamental process of layer-by-layer fabrication with photopolymer materials is common throughout each approach.

The range of photopolymer materials for 3D printing is rapidly expanding, with optical-quality transparent plastic, deformable 'rubber', and biocompatible polymers available on the market. In this work we used an Objet Eden260V 3D printer and Objet VeroClear transparent material to fabricate optical elements. VeroClear has similar optical properties to Poly(methyl methacrylate) (PMMA), commonly known as plexiglas^{TM}, with a refractive index of 1.47 (650nm light source). Several other manufacturers also provide similar transparent materials, including DSM Somos' Watershed XC 11122 and 3D Systems' Accura ClearVue.

The Objet Eden260V has a print resolution of 600 dpi (42 microns) that is significantly higher than fused deposition modeling (FDM) 3D printers (e.g. Stratasys Dimension, MakerBot, or RepRap) that are typically around 100 dpi (254 microns). High resolution printing allows the creation of visibly smooth models without internal gaps. Model surfaces can be further enhanced with a manual finishing process to achieve optical clarity. This process consists of removing support material, sanding the surfaces with incrementally finer sandpaper, and then buffing.

Capabilities

3D printing technology enables the fabrication of custom 3D printed optical elements with unique capabilities that are otherwise difficult to achieve.

Multiple Materials Optical elements can be fabricated that combine multiple chemically disparate materials in a single model. 3D printers can often use at least two materials simultaneously: *model material* and *support material*. Model material constitutes the main model itself and support material is used as a sacrificial material to provide structural support under model overhangs and in hollow areas. Typically, support material is removed and disposed of once the printing process is finished, but can also be embedded inside the model to guide, block, and diffuse light. A third 'material' that can be utilized is *air*, hollow pockets of air can be used to guide and reflect light in a similar manner to mirrors and beamsplitters. Advanced 3D printers can combine opaque materials with optical quality transparent materials to mask and block light.

Structures within Structures As the 3D printing process is performed additively layer by layer, geometric structures can be fabricated inside other structures to create optical elements. For example, areas of transparent material can be surrounded by a material with a different refractive index, to transmit light from point to point using total internal reflection (TIR) through the inside of a model. Opaque materials printed within or around a transparent material can be used to block the transmittance of light from one section of the model to another. This can be used to seal internal compartments and avoid optical crosstalk, or to minimize light leakage from the model that may be distracting to the user.

Combined Mechanical-Optical Design 3D printed optical elements can be designed hand-in-hand with the mechanical design of a device. For example, optical elements can be integrated into the body of a device to guide light through the model, act as lenses, or house optical sensors. This combined approach enables a rich new space for prototyping physical interfaces with low-cost optical sensors, such as buttons, sliders, dials, and accelerometers. A single mechanical-optical design can greatly reduce the number of individual parts and the manual labor required for assembly. Optical fiber bundles, that are typically made up of 100s of individual fiber strands, can be 3D printed in a single pass with a solid mechanical structure.

3D printed optical elements currently have some limitations. These include issues of light transmission, surface finishing, clarity, and hollow area fabrication. We describe each of these limitations in the Discussion section. We now introduce four categories of fabrication techniques that demonstrate the wide range of uses for *Printed Optics*.

LIGHT PIPES

'Light pipes' are 3D printed optical elements, similar to optical fiber, that can be used to guide light from point to point. Optical fiber has been used in interactive systems for both display [3, 10, 18] and sensing purposes [3, 12, 20, 23, 34, 39]. Unlike conventional optical fiber, 3D printed light pipes allow arbitrary geometries to be created in software and then fabricated in a single 3D print. Simply by changing software parameters, light pipes can be created with variable widths, rounded caps, and joints with other light pipes. In contrast conventional manufacturing requires considerable effort for individual fiber optic strands to be mechanically assembled, fused/deformed with heat, or chemically bonded.

Internal light pipe geometry can be embedded inside a larger model that has its own independent form-factor, such as a character (Figure 3), mobile device (Figure 4), or tangible chess piece (Figure 5). As each light pipe can be precisely fabricated at a given location, the process of light pipe routing to avoid intersections becomes a well defined software problem. One current limitation of 3D printed light pipes fabricated on the machine we have available is imperfect light transmission with longer pipes or pipes that curve significantly. We outline the characteristics of this light loss in the Discussion section. We have designed around this limitation to produce functional prototypes, but envision our techniques can be expanded using future 3D printers that are optimized for optical performance.

Example Applications

We outline several example applications that demonstrate uses for 3D printed light pipes.

Mobile Projector Displays Mobile projectors have enabled a range of new interactive systems [6, 30, 38]. The small form-factor of mobile projectors makes them well suited to tangible accessories that can map the projector display onto arbitrary surfaces. We have developed a character accessory that uses 3D printed light pipes to guide projected light through the inside of the model and onto outer surfaces. The character is 3D printed with a grid of ⌀0.5 mm light pipes leading from its feet to its eyes (Figure 3a). We paint the outer area of the character except for the ends of the light pipes. When the feet are attached to a mobile projector, the character's eyes become a display surface, responding to user interaction such as sound or physical movement (Figure 3b).

Mobile Touch Sensing Sensing touch has become an important part of interaction with many computing devices [16, 17, 27]. 3D printing is well suited to implement touch [5] and grasp [39] sensing on and around mobile devices. 3D printed light pipes can sense touch by guiding light from arbitrary

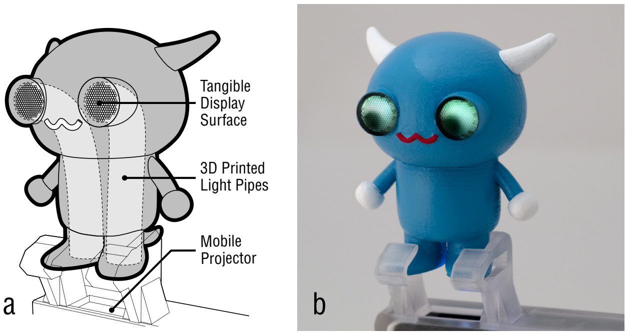

Figure 3: A 3D printed mobile projector accessory using embedded light pipes (a) to map a projected image onto a characters eyes (b).

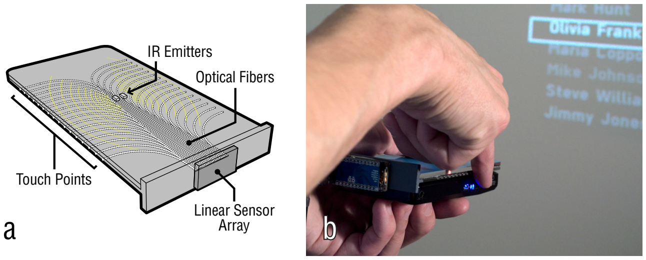

Figure 4: We envision touch sensing using 3D printed light pipes embedded in the walls of future devices. Our proof-of-concept prototype (a) attaches to a mobile projector for gestural control of projected content (b).

locations on the surface of a mobile device to a single sensor array. A key advantage of this technique is the ease with which light pipes can be printed into the walls of a device to create mechanically robust and exceptionally thin (sub mm) embedded sensing with minimal hardware assembly.

We have produced small scale 3D printed prototypes that demonstrate how light can be piped from a 1.5 mm touch point onto a 0.336 mm section of a CCD sensor. When scaled to the size of typical mobile devices however, light loss with 3D printed light pipes currently impacts upon sensing performance. As a proof-of-concept prototype we instead use conventional optical fiber embedded in a 3D printed case to simulate this sensing technique. We arrange 32 'light pipes' so they are exposed on the sides of a mobile projector and piped back to a single 128 pixel photosensor array (Taos TSL202R). The TSL202R is capable of frame-rates up to 40,000 hz for extremely responsive touch interaction on (or near) the device surface. We use two infrared (IR) LEDs embedded in a laser-cut piece of acrylic to provide constant illumination. Figure 4a shows our proof-of-concept prototype demonstrating that the casing of a mobile projector can be embedded with light pipes for robust touch sensing. Single and multi-touch gestures can be used on the side of the device to scroll and zoom in on projected content (Figure 4b).

Tangible Displays Tangible objects have been used to extend the display area of tabletop and touchscreen surfaces with optical fiber bundles [3, 10, 18] and prisms [19]. One of the inherent problems with optical fiber is maintaining alignment with large numbers or long lengths of fiber during mechanical assembly. 3D printed light pipes avoid this issue as individual pipes can be accurately fabricated and enclosed inside a simultaneously printed rigid support structure. Optimal packing patterns can be produced in software to maximize light transmission with large display grids. Although currently the optical quality is inferior to traditional optical elements, light pipes do provide a highly accessible and customizable alternative.

We have developed a set of tangible chess pieces that display content piped from a diffuse illumination tabletop surface. A 62 x 34 grid of ⌀0.5 mm light pipes is embedded in the base of each chess piece and provides a display area perpendicular to the tabletop surface (Figure 5). Contextual information, such as chess piece location and suggested moves, can be displayed on each individual piece using display space that would otherwise be occluded. Fiducial markers cut from transparent IR reflecting film (Tigold Corporation Type 7232) are adhered to the bottom of each chess piece. Projected visible light passes through the transparent marker and into the light pipes, while IR light is reflected back to an IR camera to track and identity each chess piece.

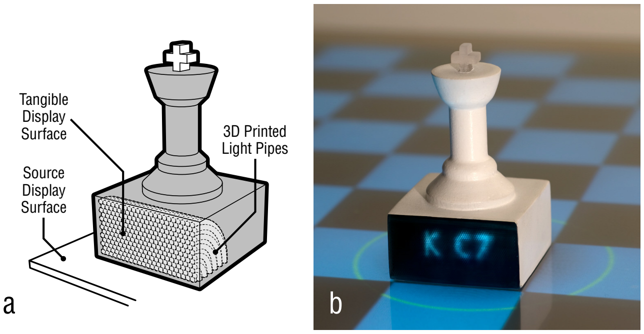

Figure 5: Light pipes are 3D printed inside tangible objects, such as chess pieces (a), to create additional display surfaces for tabletop interaction (b).

Fabrication Techniques

3D printed light pipes function in a similar manner to optical fiber with light reflecting internally as it travels along the length of the pipe. Internal reflection is caused by a difference in the refractive index of the internal *core* (through which light travels) and the external *cladding* (which surrounds the core) (Figure 6). We fabricate light pipes using model material (Objet VeroClear) for the core and support material (Objet Support Resin) for the cladding. The model material cures into a rigid transparent material and the support material into a soft material designed to be easily broken apart for quick removal. The difference in material density allows for TIR to occur. To create a mechanically sound model, we surround the brittle support material with an outer casing of rigid material. We can fabricate light pipes down to a thicknesses of ⌀0.25mm core with a cladding layer thickness of 0.084mm. To create accurate digital geometry, we programmatically generate light pipe grids using Python inside the Rhinoceros 3D application (www.rhino3d.com). This geometry can then be exported into a mesh-based format suitable for 3D printing.

INTERNAL ILLUMINATION

3D printing is known for its ability to precisely fabricate the *outer* form of physical objects and has been used to create a variety of unique displays [1, 2, 29, 36]. Optically clear material allows for the design and fabrication of *inner* forms

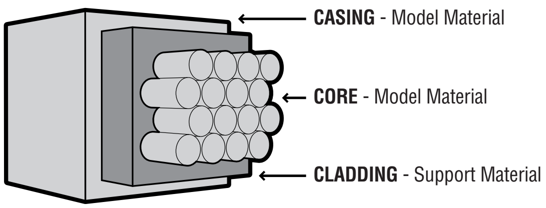

Figure 6: Light pipes consist of a rigid transparent core, a soft cladding, and a rigid outer casing.

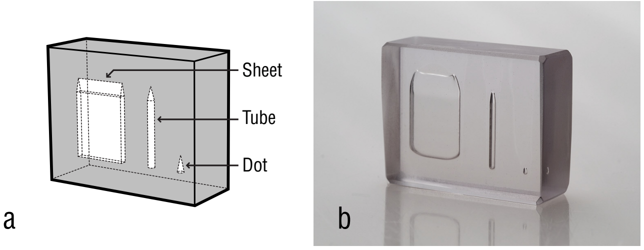

Figure 7: *Sheets*, *tubes*, and *dots* are primitive elements for fabricating reflective pockets of air inside a 3D print. Due to material settling, digital geometry (a) differs slightly from the actual printed form (b).

within a 3D printed model. Internal structures can be viewed from the outside and highlighted with illumination. Internal illumination can be used with interactive devices to display information ranging from simple indicators to complex volumetric displays. In this section of the paper we introduce techniques for internal illumination by creating reflective pockets of air within a solid transparent model.

Example Applications

We outline several example applications that demonstrate uses for internal illumination.

Volumetric Displays 3D printed internal structures are an enabling technology for static-volume volumetric displays, allowing precise alignment of 3D pixels within a volume. Although volumetric displays have been implemented in a number of ways [9, 25], 3D printing allows a new level of control over the shape, size, and resolution of the display. Using the versatility of 3D printing, we implemented a volumetric display based on *Passive Optical Scatterers* [28].

We explored a mobile form factor for a volumetric display by embedding an 4 x 8 x 11 array of ⌀1.2 mm *dot*-shaped air pockets (Figure 7) inside a 40 x 80 x 50 mm volume of transparent 3D printed material (Figure 8). The display is mounted to a laser-based mobile projector (Microvision ShowWX+). 32 x 32 pixel blocks are used to address each of the dots inside the volume. 2D pixel blocks are mapped to 3D dots using a Z axis depth map. An automated camera calibration routine is used to compensate for any slight mechanical misalignments.

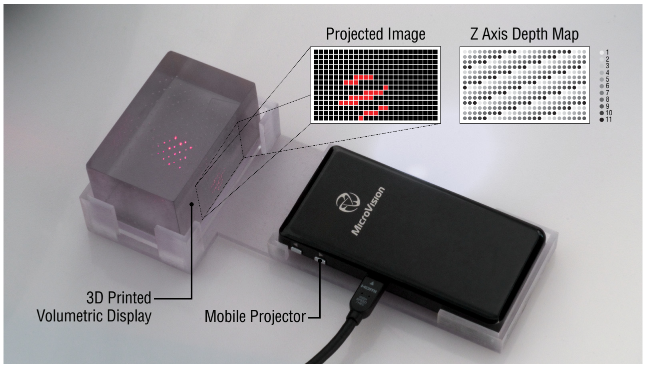

Figure 8: A mobile volumetric display created with embedded *dots* of air inside a 3D printed volume. A sphere is displayed inside the volume by remapping 2D pixels using a Z axis depth map.

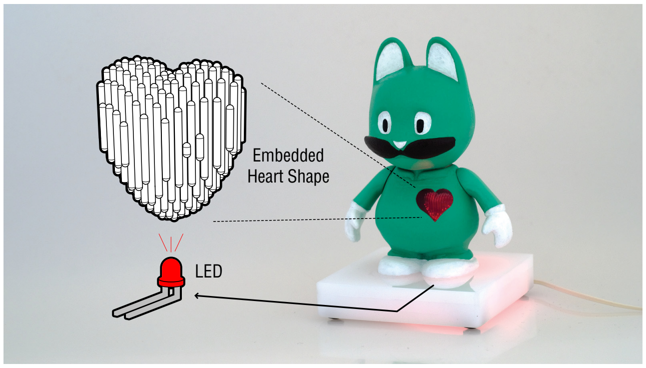

Figure 9: A toy character with an embedded heart shape made from *tubes* of enclosed air and illuminated with an LED.

Internal Patterns 3D printed *tubes* are hollow cylinder-like structures printed vertically (Figure 7). Tubes are particularly well suited to represent arbitrary shapes inside a 3D printed model. Because it is not yet possible to enclose arbitrary hollow shapes (due to issues of overhang and support material extraction), tubes represent a useful approximation. We created a toy character with a glowing heart embedded inside (Figure 1b). The heart is made from a set of hollow tubes packed together and illuminated from below with an LED (Figure 9). Although a simple example, the internal structures are very difficult to achieve with other manufacturing techniques. We found that tubes can be reliably created down to ⌀0.6 mm and packed together with a minimum distance of 0.6 mm between tubes. This enables relatively good resolution to represent arbitrary internal shapes.

Internal Text 3D printed *sheets* are flat rectangular air pockets that can be used to approximate lines (Figure 7). Text within a 3D printed structure can be fabricated to create robust signage that is resistant to impact and everyday wear. The optical clarity of the material makes it possible to view internal text under normal daylight lighting conditions or with illumination at night. Using 3D printed sheets to fabricate internal text, we created a nixie tube style numeric display (Figure 10a). Individual 3D printed layers with embedded numbers are mounted together and side-illuminated using either an LED or a mobile projector (Figure 10b).

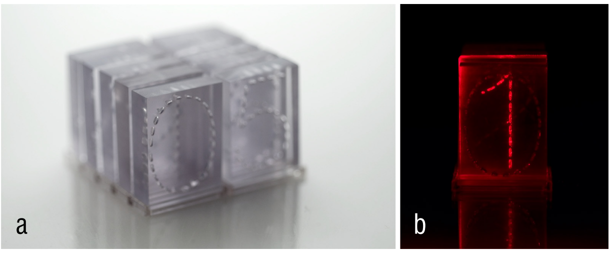

Figure 10: A numeric display (a) created with hollow *sheets* of air that reflect light when illuminated (b).

Fabrication Techniques

By creating enclosed pockets of air within a solid transparent model, light intersects with these air pockets and is transmitted or reflected depending on the angle of incidence. By carefully designing the geometry of the air pockets light can be guided internally within the model or externally out towards the users eye. Air pockets can be created using 3D printers that deposit small beads of material layer-by-layer to build up a model. As individual beads of material are deposited, they must have a supporting surface beneath them or they fall down with gravity. However, a small amount of step-over (overhang) from layer to layer allows for hollow areas to be slowly closed. In practice a step-over angle equivalent to 14°from vertical allows air pockets to be reliably closed with minimum shape distortion. Greater step-over angles cause the material to fall into the air pocket and slowly raise the air pocket location vertically or fill it entirely. Figure 7 shows a series of primitive elements that can be fabricated from air pockets. The digital geometry sent to the printer (left) differs from the actual air pocket shape fabricated (right). This difference is due to beads of material settling without direct support structure during the fabrication process. To programmatically generate patterns from the *dot*, *tube*, and *sheet* primitives, we use the Grasshopper environment (www.grasshopper3d.com) inside Rhinoceros. This allows primitive elements to be mapped to lines, enclosed within solids, or aligned with illumination sources.

SENSING MECHANICAL MOVEMENT

Optical sensing of mechanical movement has been achieved in a number of form-factors [8, 15, 31, 35, 37]. Our approach uses 3D printing to create custom optical sensing embedded in interactive devices. We use low-cost IR emitter/receiver pairs, to sense common user inputs such as rotation, push, linear movement, and acceleration. Our approach offers several benefits. Firstly, custom sensors can be designed and prototyped with minimal effort. 3D printed sensors allow convenient, fast, accurate, and repeatable sensor fabrication. In many cases only a generic IR emitter-receiver pair are required on the electronics side. Secondly, custom sensors can be embedded in the casing or mechanical structure of a device. This enables sensing of user input through the walls of a device, greatly simplifies hardware assembly, and produces robust high fidelity prototypes.

Example Applications

We introduce example applications that demonstrate how 3D printed optical elements can be used to detect common mechanical movements.

Sensing Displacement We have developed a library of mechanical movements that can be mapped to a displacement sensing scheme. In this scheme a flexible light guide mounted below the surface of a device is physically displaced to change the amount of IR light traveling between an emitter-receiver pair (Figure 11, 13a). Displacement sensing provides a versatile way to sense a number of user inputs with 3D printed optical elements.

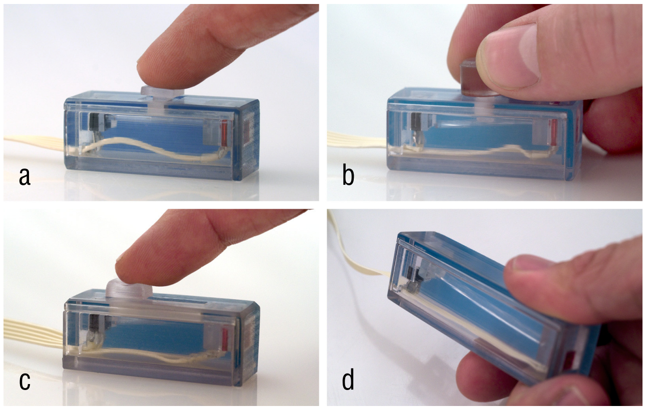

Figure 11: User inputs such as push (a), rotation (b), linear movement (c), and acceleration (d) can be sensed by the displacement of a 3D printed light guide.

We sense *push* and *pressure* with a button that applies linear force to displace the light guide (Figure 11a). As the user presses the button the receiver changes from a high to a low state (Figure 13a). Elastic deformation causes the light guide to return to a high state when the user releases the button. The elasticity of the light guide provides clear haptic feedback that can be accentuated with small surface detents on the button shaft.

We sense *rotation* with a screw dial that gradually lowers to displace the light guide (Figure 11b). When fully inserted the receiver returns a low signal and returns to a high state as the screw dial is extracted. Custom thread pitches can be designed for precise control over how quickly the screw dial transitions between the two extremes.

We sense *linear movement* with a mechanical slider that depresses the light guide when moved from one side to the other (Figure 11c). The light guide is angled downward so that it rests just below the slider at one end and is above the slider at the other end. As the slider is moved by the user, the light guide is displaced to register a low reading.

We sense *acceleration* by printing extra material on the end of a light guide to enhance the effects of outside motion (Figure 11d). The extra weight causes the light guide to be displaced when the the user moves the device along an axis perpendicular to the light guide. The effects of gravity can also be perceived, as the weighted light guide slumps downwards causing displacement.

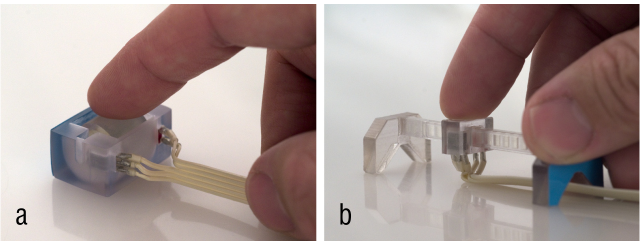

Figure 12: Rotary motion of a scroll wheel (a) and linear motion of a slider (b) can be sensed with IR light passing through 3D printed mask material.

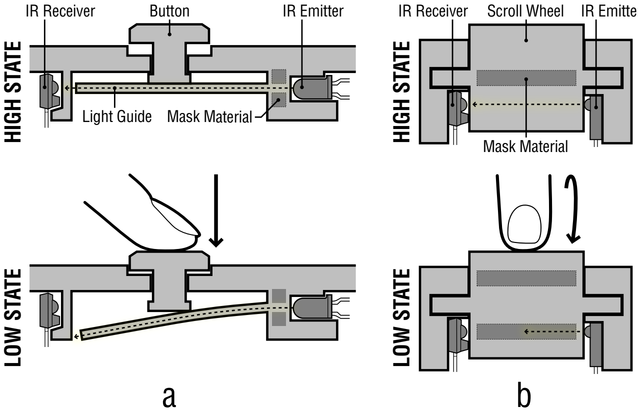

Figure 13: Mechanical force moves a 3D printed light guide below a button (a) and a rotary encoder pattern within a scroll wheel (b) from a high state (top) to a low state (bottom).

Sensing With Encoders We fabricate custom linear and rotary encoders with 3D printing by creating a mask pattern from two different materials and sensing the change in light transmission through each material as the encoder moves.

We sense *scroll wheel* motion by embedding sections of mask material in the body of a scroll wheel (Figure 12a). An IR emitter-receiver pair are mounted in the scroll wheel housing on either side. As the scroll wheel is turned, a high-low pattern is returned by the receiver that can be decoded into a relative rotation value based on the mask pattern design. More complex absolute encoding schemes can also be achieved using the same basic principle with multiple emitter-receiver pairs.

We sense *slider* motion by embedding a mask pattern into the shaft holding the slider (Figure 12b). An IR emitter-receiver pair are mounted inside the slider housing on either side of the shaft. As the user moves the slider a high-low pattern is returned to the receiver.

Fabrication Techniques

Sensing Displacement Our displacement sensing scheme uses transparent material to create a flexible light guide between an IR emitter-receiver pair. Light from the emitter travels through a small aperture surrounded by light-blocking mask (support) material and reflects inside the light guide until it meets the receiver. In its normal state light travels into the receiver to register a high reading (Figure 13a, top). The light guide can be displaced with mechanical force, causing the receiver to register a lower reading (Figure 13a, bottom). A range of intermediate values are returned between these two states. In all cases the flexible light guide is positioned just below the surface of the sensor housing and mechanically displaced by outside force. Emitters and receivers are inserted into the housing walls with precisely aligned slots.

Sensing With Encoders To create rotary and linear encoders we use an IR emitter-receiver pair mechanically mounted on either side of a rotary shaft/linear rail. A 3D printed mask pattern is embedded into the rotary shaft/linear rail to produce signal changes. The mask pattern is created with embedded support material so that a distinctive change in light intensity is registered by the receiver. Figure 13b illustrates the high (top) and low (bottom) states of a rotary encoder.

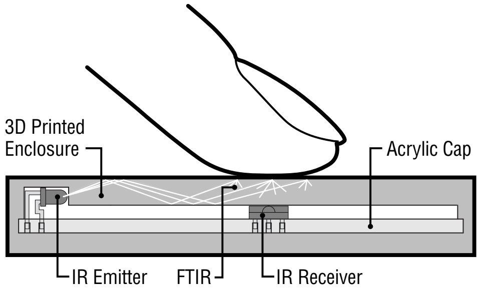

Figure 14: FTIR touch sensing embedded within a 3D printed enclosure.

We use standard 3mm or side-look (Honeywell SEP8706) 940nm IR LEDs and light-to-voltage sensors (Taos TSL260R) as the emitters and receivers for both displacement and encoder sensing in this section. Modulation of the emitter-receiver pair would provide further robustness to varying ambient light conditions.

EMBEDDED COMPONENTS

As 3D printing technology grows in sophistication, we envision it will be possible to automatically 'drop-in' components during the fabrication process [4, 22, 33], using part placement robots similar to those employed for PC board manufacture. Drop-in embedded components are physically robust, enable tight mechanical tolerances, and allow easy compartmentalization. Combining optical components with transparent materials allows sensing, display, and illumination to take place through the casing without exposing components directly on the surface of a device. Eventually, we envision it will be possible to 3D print electronic components in their entirety [7, 26]. Although it is not yet possible to automatically insert or print electronic components on commercial 3D printers, it is possible to simulate the results of embedded optical components by manually inserting them during the print process. In this section of the paper we introduce a number of techniques for designing, fabricating, and interacting with optoelectronic components embedded in transparent 3D printed enclosures.

Example Applications

We introduce example applications that demonstrate uses for 3D printed optical elements with embedded optoelectronic components.

Embedded FTIR Sensing Frustrated total internal reflection (FTIR) based sensing is known for its robust and precise touch-sensing performance. Typically individual components are mounted alongside an optical surface that users interact with [13, 17, 27]. In our approach we embed components inside the optical surface to produce a very robust and completely enclosed FTIR implementation. In a basic configuration, an LED emitter is embedded in a hollow area within the 3D print and light is emitted directly into a flat sensing surface (Figure 14). An IR receiver is mounted perpendicular to the sensing surface and detects light reflected

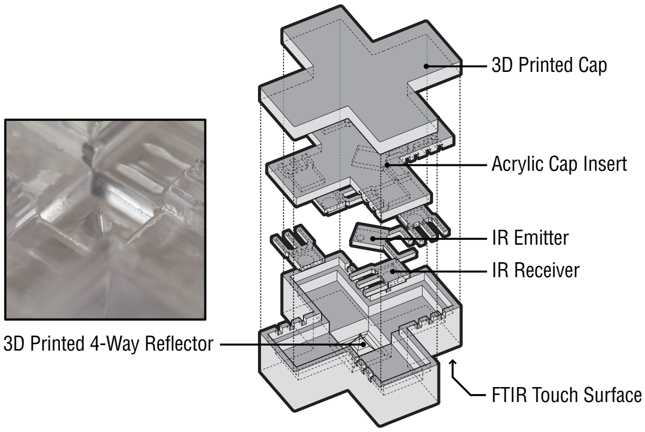

Figure 15: Exploded view of a D-pad made with embedded optoelectronic components. A 3D printed 4-way reflector is used to direct light into a custom shaped FTIR touch surface.

by fingers coming into contact with the outer surface. A more complex variation of the same sensing technique is shown in our four-way D-pad sensor (Figure 1d). A flat side-look LED (Honeywell SEP8706) is embedded facing a four-way reflector that splits light towards four embedded IR receivers (Taos TSL260R) (Figure 15). An analog touch reading is measured at each of the sensors. As with standard FTIR an approximate measurement of pressure is returned based on the amount of skin contact and light reflectivity.

Lenses We embed optoelectronic inside 3D printed plano-convex and plano-concave lenses to better control the directionality of illumination or optical sensing. The base of the 3D print makes up the planar side of the lens and the curved lens surface is fabricated below the component then smoothed with extra layers of material deposition. Figure 16 shows two identical LEDs embedded with 3D printed plano-convave (a) and plano-convex (b) lenses.

Beamsplitters We fabricate rudimentary beamsplitters by creating prisms in front of embedded components. Based on the angle of incidence, some light passes through the prism and the remainder reflects off in another direction. Figure 16c shows an LED with light being split in two directions by the embedded prism.

Fabrication Techniques

We manually insert optical components during the 3D printing process in a similar manner to [22]. The digital geometric model is designed in such a way that a hollow area is left for the component to be inserted. Support material printing must be disabled to ensure that it is not deposited inside the component area. If the component is inserted flush with the top of the model, printing is continued to completely enclose it inside. If an area of air is desired around the component, a laser cut transparent acrylic ‘cap’ is affixed above the component to seal it in before printing continues (Figure 17).

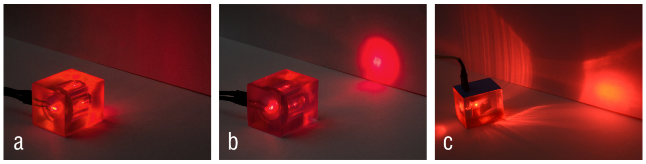

Figure 16: Two identical LEDs are embedded with a 3D printed plano-concave (a) and plano-convex (b) lens. A beam-splitter sends light in two directions (c).

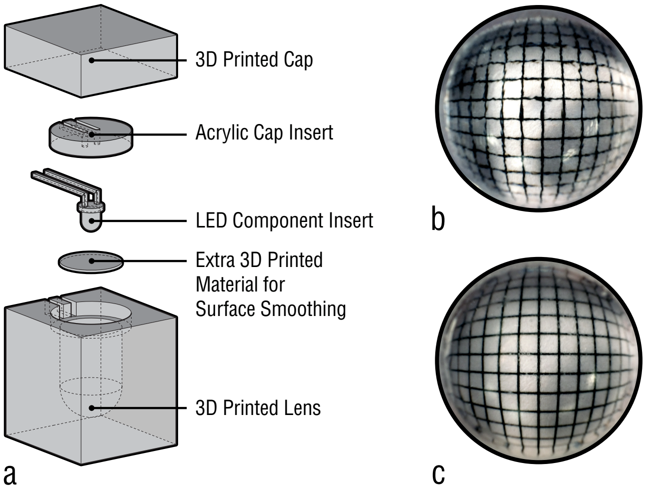

Figure 17: Optoelectronic components are inserted, capped, and enclosed inside a 3D printed model to create a custom lens (a). The quality of the lens surface finish (b) can be improved by depositing additional uniform layers of material (c).

Hollow cavities created for components do not have an optically clear finish (Figure 17b) and it is not practical to sand or buff these small cavities during the print process. However, we discovered a unique technique to improve the surface quality of cavities by depositing additional uniform layers of material. This material is deposited from above and falls into the cavity in a liquid state to smooth its surface. Figure 17c shows the improved surface finish achieved when ten additional layers of material are deposited.

DISCUSSION

3D printed optical elements have unique limitations that should be considered during the design and fabrication process.

Light Pipe Transmission

3D printed light pipes fabricated with our current setup suffer from limited light transmission. To more accurately characterize the conditions under which light loss occurs, we performed light measurement tests with light pipes over varying distances and curvature. To simulate a typical application scenario we used off-the-shelf components: a red 5mm LED emitter and a photodiode-based receiver (Taos TSL12S). For each reading, light was directed into the light pipe with the emitter and a voltage value measured from the receiver at the other end. The emitter and detector were coupled to the test pieces using custom slots, similar to those shown in Figure 11-13, and without surface finishing.

For the distance test we compared the light transmittance of a ⌀2mm 3D printed light pipe, to a commercially produced

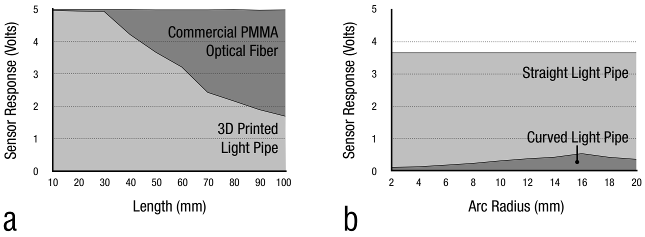

Figure 18: Light transmittance of 3D printed light pipes compared to commercial optical fiber (a) and transmittance of 50mm 3D printed light pipes in 90°arcs with increasing curvature radius (b).

⌀2mm optical fiber made of PMMA. The 3D printed light pipes consisted of a core, cladding, and casing configuration with distances ranging from 10-100mm in 10mm increments. The commercial optical fiber was cut to the same lengths and mounted in a rigid casing. For the curvature test we created a series of light pipes following a 90°arc, each with an incrementally larger radius. The length of the light pipes was extended on each end to be precisely 50mm in total length.

Figure 18a shows that 3D printed light pipes currently suffer from increasing light loss with distance. Adding curvature to a light pipe further increases light loss when compared to a straight light pipe of equal length (Figure 18b). We believe this limited performance is due to two factors. Firstly, the contours where two different materials intersect are currently not perfectly smooth (Figure 19). Microscopic unevenness on internal surfaces result in light being lost or redirected in unpredictable ways. However, we found the consistency between ten identical 50mm straight prints to be high, with a standard deviation of 0.0822V when measuring transmittance as previously described. Secondly, although we know the refractive index of the core material, no information is available for the refractive index of the cladding material. Because we use support material that is not intended as an optical material, its performance as cladding is understandably low. We can assume that the refractive index of each material is close enough to restrict the angle of incidence to a relatively small value and thereby limit internal reflection.

Although the current materials and printing process we use are not optimized for optical performance, promising materials science research has demonstrated that photopolymer waveguides can be fabricated in both planar [14] and non-planar [24] forms with minimal light loss. We are therefore optimistic about the possibilities for fabricating light pipes in the next generation of optically optimized 3D printers. It is worth noting that many commercial display technologies routinely encounter significant light loss, e.g., resistive touch screens reduce display light transmission by up to 20% [11].

Surface Finishing

In current generation 3D printers, unfinished surfaces appear smooth and transparent to the naked eye, but not optically clear. Unfinished surfaces can be used when some amount of light scattering is acceptable, however to maximize light passing to/from the interior of a 3D printed optical element, surface finishing should be performed (i.e. sanding and buffing). Flat surface finishing can be performed using power tools such as a belt sander and buffing wheel. Curved surfaces require hand sanding and are more time intensive. Textured surfaces or surfaces with small micro-facets are difficult to perform finishing on without specialized equipment. Internal surfaces can generally not be reached to perform manual surface finishing, but applying additional layers of uniform material cover can improve the quality of the surface (Figure 17c).

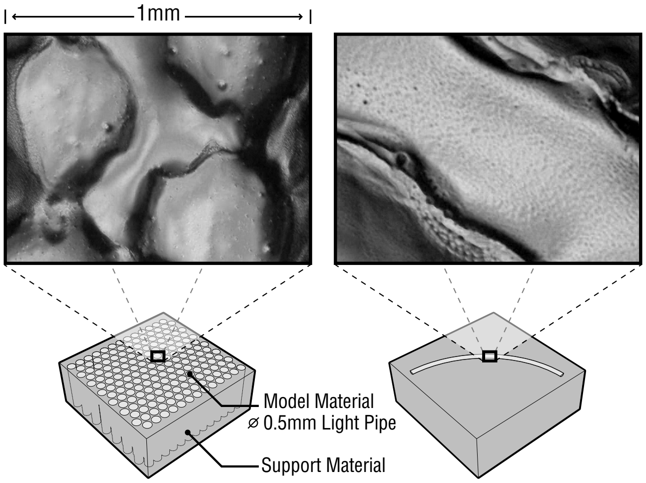

Figure 19: Magnified view of the material intersections in 3D printed light pipes.

Clarity

Based on our experiences with the Objet Eden260V, we have found that the clarity of 3D printed optical elements currently depends on several factors. *Model Thickness*: thicker models tend to lose optical clarity and appear increasingly cloudy. *Print Direction*: the greatest clarity is seen when looking perpendicular to the printed layers, looking parallel to the printed layers appears blurrier. *UV Exposure*: Overexposure to UV light during the curing process can cause a loss in optical clarity, making the model appear yellow in color. *Surface Quality*: greater clarity can be achieved with extra sanding steps during the finishing process.

Hollow Areas

As 3D printed objects are built up layer by layer, hollow areas typically require support material inside the hollow. Printing completely enclosed hollow areas can seal the support material inside with no means for it to be extracted. Completely enclosed hollow areas of air can be fabricated using jet deposition-based machines by disabling support material and using internal geometry with minimal step-over in the vertical axis. This requirement for self-supporting geometry limits the design space when creating hollow areas. In theory, internal geometry can be combined with arbitrary external geometry complete with overhangs and support material. In practice, the 3D printer we made use of did not allow selective use of support material; it must be either enabled or disabled for each print. This restriction, however, can be resolved with an improved software interface to the 3D printer.

Despite these limitations, by demonstrating the capabilities and application space for *Printed Optics*, we hope to influence the design of future 3D printing systems that are fine tuned for optical applications.

CONCLUSION

We have outlined the *Printed Optics* approach for using 3D printed optical elements embedded in interactive devices. *Printed Optics* enable many new possibilities for interactive devices and this initial exploration introduced a range of techniques for sensing, display, and illumination. With the continuing emergence and accessibility of 3D printing technology, we believe 3D printed optical elements will become an important part of future interactive devices that are printed rather than assembled. We foresee future 3D printers with a diverse range of optical printing functionality. The ability to dynamically control optical properties such as the refractive index, reflectivity, transmittance, absorption, and diffusion will enable an even richer design space for sensing, display, and illumination. Although that time is not upon us yet, *Printed Optics* demonstrates what is possible today.

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