PAPILLON: Designing Curved Display Surfaces With Printed Optics

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ABSTRACT

We present a technology for designing curved display surfaces that can both display information and sense two dimensions of human touch. It is based on 3D printed optics, where the surface of the display is constructed as a bundle of printed light pipes, that direct images from an arbitrary planar image source to the surface of the display. This effectively decouples the display surface and image source, allowing to iterate the design of displays without requiring changes to the complex electronics and optics of the device. In addition, the same optical elements also direct light from the surface of the display back to the image sensor allowing for touch input and proximity detection of a hand relative to the display surface. The resulting technology is effective in designing compact, efficient displays of a small size; this has been applied in the design of interactive animated eyes.

ACM Classification: H.5.2 [Information interfaces and presentation]: User Interfaces - Graphical user interfaces; Input devices and strategies.

Keywords: 3D printing, fabrication, touch sensing, finger input, gestures, interactive characters, alternative displays.

INTRODUCTION

There has been rapidly growing interest in departing from traditional flat rectangular paradigm of todays display technology, and in exploring alternative display forms and shapes for interactive applications. These include but are not limited to, the design of spherical, polyhedra and volumetric displays [2, 3, 9, 13, 21, 24], the exploration of bendable, deformable and elastic displays [23, 17, 18, 7] as well as actuated displays that change their shape dynamically [14, 19, 20].

PAPILLON is a technology for designing *3D curved display surfaces* that both act as information display and sense two dimensions of human touch. There are formidable challenges in designing curved visual displays. Traditional displays commonly used in consumer electronic devices such as liquid crystal displays (LCD), can not be easily manufactured as arbitrary 3D shapes. Flexible displays, such as organic light emitting displays (OLED) and electrophoretic displays [17] can be bended and twisted, but can not be formed into an arbitrary shape, e.g. a spherical cap. Projecting images onto curved screens allows for the display of various forms [3, 5]. However, due to the size of a projectors, focal length and the need for an unobstructed optical path, it is often difficult to use them in small devices, e.g. interactive characters and toys. Additionally, enhancing all these approaches with touch sensitivity introduces yet another level of complexity and design challenges.

Figure 1. Curved displays are embedded into the characters to design interactive eyes. The characters are passive and do not have any electronics embedded.

PAPILLON addresses many of these challenges by exploring a recently proposed *printed optics* approach [26], where the surface of display is constructed as an array of printed optical elements, i.e. 3D light pipes, that direct images from an image source to the surface of the display (Figure 1). The choice of the image source is arbitrary and it could be a traditional projector or an LCD screen. Crucially, the display surface and display driving electronics are effectively *decoupled,* which allows arbitrary curved display surfaces to be designed and iterated without modifying the conventional planar image source. In addition, the same optical elements can also direct light from the display surface to an image sensor allowing position and proximity of user hand to be tracked. Touch, proximity and position sensitivity of *PAPILLON* is an important contribution of this work.

PAPILLON represents a significant new application and development of *Printed Optics* that further explores its vi-

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sion of creating tools for designing highly customizable interactive devices. The original printed light pipes displays described in [26] were limited to flat surfaces. As we discuss later, designing curved display surfaces with printed optics technique is a not a trivial problem. This is due to the fact that classic square pixel grids can not be remapped onto a curved surface without introducing significant image distortions. Investigating, designing and implementing the algorithms that allow to compute pixels arrangements for curved display surfaces is a contribution of this paper.

The design of *PAPILLON* was motivated by a specific application: designing highly expressive animated eyes for interactive characters, robots and toys. Expressive eyes are essential in any form of face-to-face communication [3] and designing them has been a challenge [1]. *PAPILLON* provides effective and efficient solution to this challenge.

The rest of the paper describes the design of the *PAPILLON* approach and it's contributions are as follow:

1. A set of fundamental techniques for producing spherical display surfaces using printed optics approach and alternative, non-rectangular pixel arrangements.
2. A technique for bi-directional touch, position and proximity sensing on curved surfaces using printed optics.
3. An application of display and sensing for designing animated eyes in interactive characters and toys.

RELATED WORK

There is a rich history of exploring display shapes in designing user interfaces. Some of the relevant explorations include volumetric displays [9], non-planar displays such as spherical, cubic or polyhedral [3, 21, 24], displays distributed in environments [22], collocated or embedded in everyday objects [11], actuated displays that change their shapes dynamically [7, 19, 20] and even biological displays where the change of appearance of biological species is used as a display modality [6, 16]. The overall goal is to find new forms for effective information presentation, exploring novel aesthetic qualities or designing displays appropriate for specific application limitations.

One of the key challenges in designing and exploring alternative display form-factors is creating technologies to display information on non-planar, *curved surfaces*. In this paper we will discuss the two classes of curved displays:

Ruled display surfaces are those that can be produced by sweeping a single line in Euclidean 3D space. Intuitively they can be understood as surfaces that could be produced by bending and twisting a flat plane, such as a sheet of paper, without tearing or stretching it (Figure 2).

Doubly curved display surfaces are those that can produce arbitrary surfaces with curves across both surface subdivision directions, such as spherical or parabolic shells.

There are three technological approaches that can be used to create curved displays surfaces. First, is *projection* on the curved or flexible surfaces [3, 5] which allows for the creation of an arbitrary display surface but requires embedding the projector in the device limiting the applications of these displays. Second, *assembling curved surfaces* out of smaller planar displays or even single pixels [24, 22, 21] which limits the resolution and form factor of the displays and has high design complexity. Third, using flexible displays to create desired shapes [11] which allows for high quality displays, but is limited to ruled display surfaces. In this paper we introduce a fourth approach, which is designing curved display surfaces using *3D printed optical elements*, which allows for the creation of both ruled and spherical display surfaces and unlike projection based curved displays it can be used with a variety of display devices, e.g. projectors, tablet computers and interactive tables. We chose to use spherical cap as a step towards arbitrary doubly curved surfaces, which we have not yet resolved.

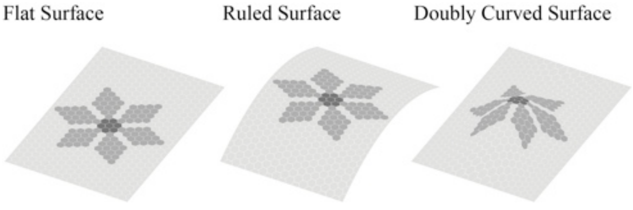

Figure 2. Classes of curved display surfaces.

Implementing touch and gesture sensitivity is another challenge in designing curved display devices. Traditional touch sensing techniques, i.e. projective, capacitive, optical or acoustic surface waves were designed for flat surfaces and fail on the irregular shaped displays. Computer vision techniques based on infrared illumination, FTIR and depth tracking are effective [1, 27], but require a clear optical path from the user touching the surface to the vision sensor, i.e. it has to "see" the curved surface. This could be a limiting factor, e.g. it makes it difficult designing interaction with very small curved displays. Recognizing touch and gesture events from sound is another possibility, but it does not allow precise position tracking [10]. Creating overlay sensors for curved surfaces has also been proposed [12], but in many cases it obstructs the surface or introduces significant additional complexity. The most relevant touch sensing approach is using embedded optical pathways between object surface and the sensor, so that the user touch could be seen "through" the object [7, 15, 28]. In *Papillon* we use the same 3D printed optical structures both for display and touch sensing, making sensing completely seamless and requiring very little instrumentation of the device.

Multiple applications of curved displays were proposed, including data visualization and group interaction, innovative interfaces for consumer electronic devices, advertisement, labeling and packaging [3, 11, 17, 21, 24]. The current work was motivated by challenges in designing animated eyes for interactive characters, toys and robots. The classic approach to designing eyes, in the movie and location-based entertainment industry, is to build mechanically actuated, animatronic eyes [1] that tend to be realistic but complex, expensive and difficult to scale down to fit into small characters, where space for motors and driving electronics may not be available. Furthermore, the animatronic approach is not applicable to fictional characters from animated movies, comics and cartoons whose eye expressions are non-realistic and highly exaggerated.

Rear-projection images of eyes and faces allows for the design of animated and highly expressive eyes for large-

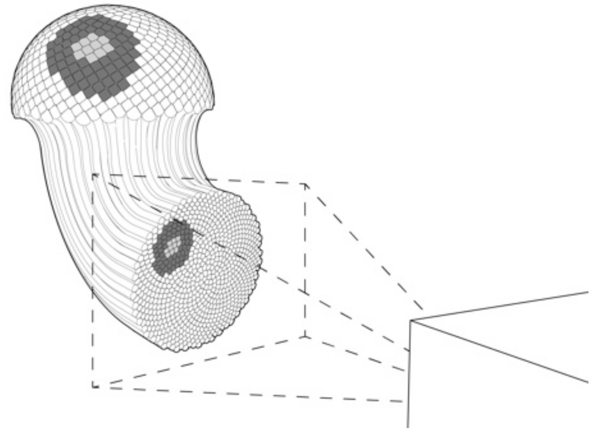

Figure 3. *Papillon* curved display design.

scale characters and robots [3]. It is, however, not scalable to small characters due to limited space. Furthermore, popular characters often take on a broad variety of appearances, from a talking sea sponge to a chameleon, with complex faces and bodies, where eyes could be sunk deep inside or stick out. Designing free air optical paths for these characters is difficult and often impossible unless we can design a technology that can effectively guide light between any two locations on the body of the character. The *Papillon* technology allows us to achieve that.

PAPILLON CURVED INTERACTIVE DISPLAYS

Papillon provides curved display surfaces using printed optics technology [26]. The surfaces are 3D printed as bundles of light pipes using transparent UV cured photopolymers separated by a translucent support material. The light pipes guide images from the receiving end of the bundle to the top of the surface (Figure 3).

The key advantage to this approach is that the design of the curved display surface is largely *decoupled from the image source* allowing for the use of projectors, LCD and OLED displays, LED arrays, laser projectors, etc. Another important advantage of this approach is that it allows for *spatial separation* of the image source and displayed image, which is important when designing embedded displays for small objects such as interactive characters (Figure 1).

Early explorations of the printed optics demonstrated feasibility of this approach but were limited to *planar surfaces*. Extending it to curved displays, however, is not trivial. It requires consideration of pixel topologies that allow to 1) transmission of images with minimum distortion and 2) allow effective packing of 3D light pipes.

Designing Light Pipes Topologies

The fundamental challenge in *PAPILLON* is designing an arrangement of pixels on a spherical display surface that satisfies the following requirements:

Isotropic pixel arrangements on a surface, i.e. the distances between all neighboring points on both input and output surfaces have to be uniform. On the receiving side it would sample the provided image uniformly. On the display side it would produce a consistent, uniform image with minimal gaps or distortions.

Isomorphic mapping between pixels on a sampling plane and pixels on the curved surface, in particular the relative arrangement and order of pixels on the bottom should correspond to the same arrangement and order on the top. This way we can assume that the image is undistorted, e.g. not reversed when displayed on the curved surface.

Pipes diameter and spacing must be within the tolerances that are possible with current 3D printing technology.

Design of the isotropic pixel arrangements depends on the properties of the geometric surface and will be different for ruled and spherical surface design.

Pixel topologies for ruled display surfaces.

Ruled display surfaces can be remapped to the plane surfaces without tears and stretching and, therefore, any classic 2D lattice, can be effectively used for pixel arrangements. A 2D Bravais lattice is a set of points created by generative discrete translations operations defined as:

$$\Lambda = n_1 \cdot \overrightarrow{a_1} + n_2 \cdot \overrightarrow{a_2} \qquad (1)$$

where n_1 and n_2 are any integer number. It was demonstrated that there are only five types of lattices defined by Equation 1: oblique, rectangular, rhombic, hexagonal, and square [4]. These five latices represent basic pixel topologies for ruled display surfaces, e.g. Figure 4 and the middle character on Figure 1 demonstrate the surfaces based on rectangular and hexagonal lattices.

Pixel topologies for doubly curved surfaces.

There are no standard lattices that are effective for any arbitrary doubly curved surfaces, each pixel arrangements has to be designed individually for each surface. In this paper we develop pixel arrangements for *spherical display surface* that is one of the most common surfaces used in broad variety of applications [e.g. 3, 23].

Traditional rectangular lattices (Equation 1) produce significant distortions when mapped on spherical or general doubly curved surfaces, the resulting points will not be

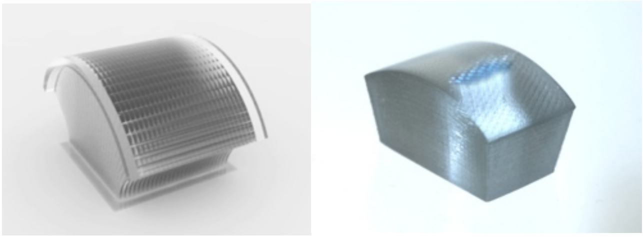

Figure 4. Ruled display surfaces with square (left) and hexagonal (right) pixel arrangements.

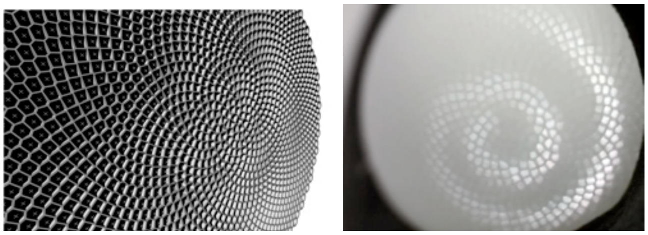

Figure 5. spheric display surfaces with Fibonacci pixel arrangements.

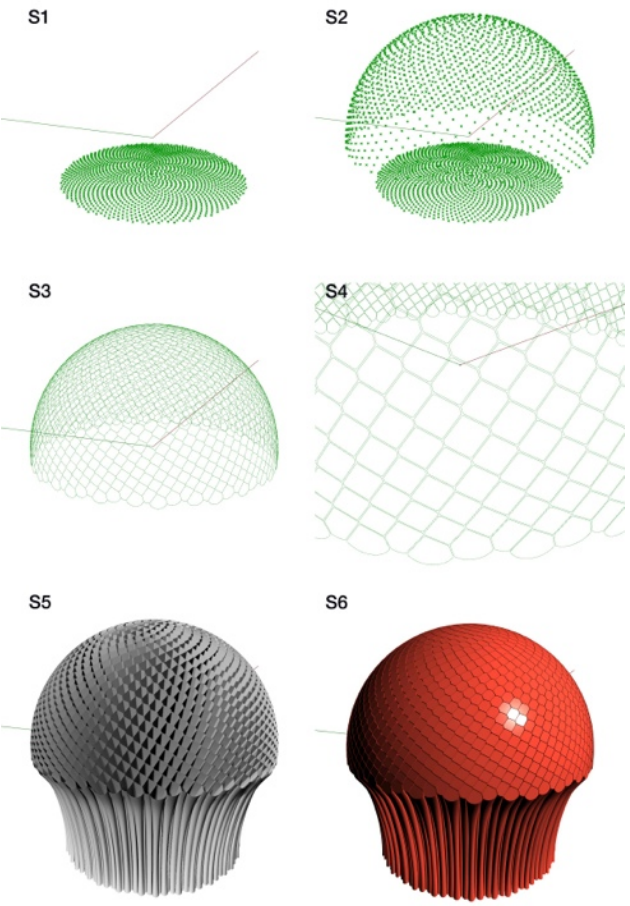

Figure 6. *PAPILLON* production pipeline.

spaced uniformly [7]. In computer graphics such spherical projection distortions can be controlled by warping 2D images before projection so that they appear normal when seen on spherical screen [3]. In case of printed optics implementing spherical warping in physical form is challenging and an alternative pixel topology has to be designed.

To address this challenge for spherical surfaces we use *generative Fibonacci lattices*. The points of the Fibonacci lattice are arranged along a tightly wound spiral on a sphere and can be calculated as follows [8]. Let N be any natural number and i an integer ranging from $-N$ to N. The number of points is $P = 2N + 1$ and i-th point of the Fibonacci spiral in spherical coordinates is computed as follows:

$$\begin{aligned} lat_i &= arcsin\left(\frac{2i}{2N+i}\right), \\ lon_i &= 2\pi i\phi^{-1}. \end{aligned} \tag{2}$$

The resulting pixel topology is evenly spaced occupying roughly the same area. We can easily control the density of pixels by changing N. Figure 5 demonstrates the spherical pixel topology with 756 points. This technique does not directly translate to arbitrary 3D surfaces and part of our future work includes integrating methods such as simulated annealing with our approach. However, for spherical solutions the Fibonacci pattern allows for a direct mapping of points from the 2D to 3D surface without any twisting of the pipes, i.e. the center line of the pipes are all in plane with the origin.

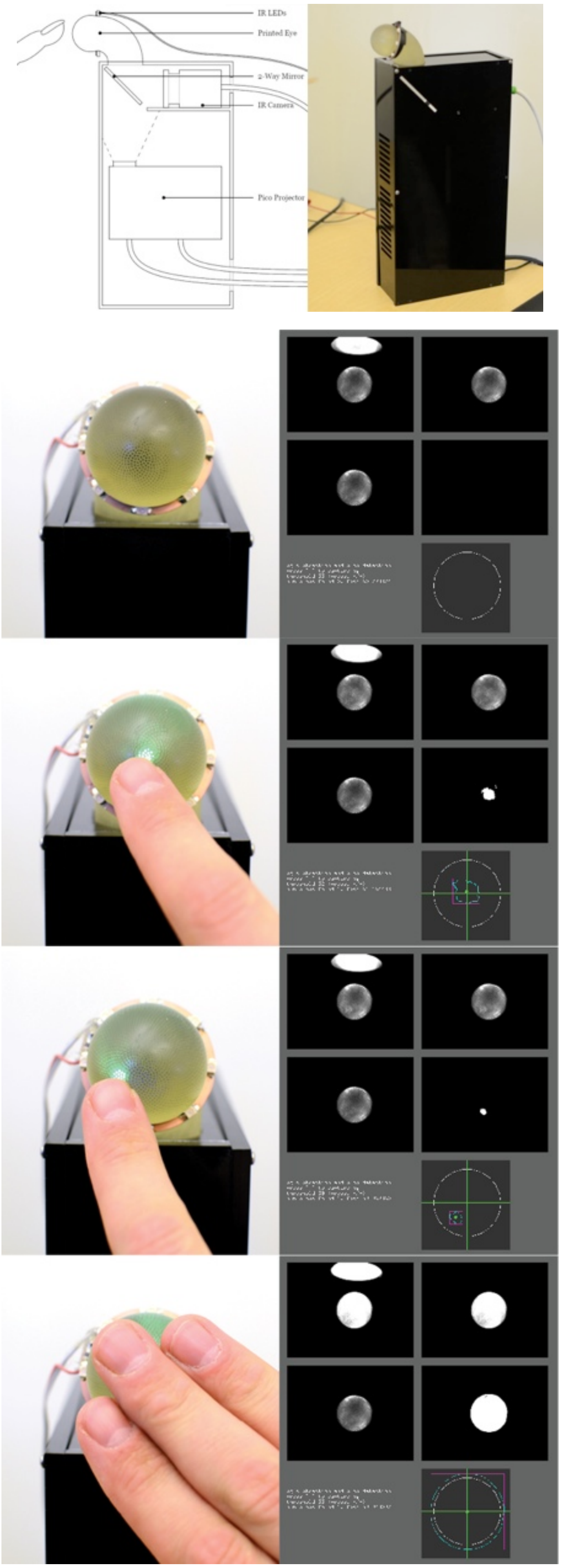

Figure 7. Position sensing on curved display

Curved Display Production Pipeline

Figure 6 outlines a basic production pipeline for spherical, curved display surfaces. All geometric computations were performed using Rhino 5.0 3D modeling environment extended with Grasshopper 9 parametric modeling toolset. Each step in the pipeline were computed using custom written Python scripting component.

In *Step 1* the pixel distribution is computed on the planar surface using Equation 2. This pixel distribution forms the base of the pipelines that is used to sample images to be displayed on the curved display surface. In *Step 2* the pixel distribution is computed on the spherical surface using the same Equation 2. Note that pixel clouds computed on Step 1 and Step 2 are isomorphic.

The Voronoi tessellation of the spherical surface is computed in *Step 3* forming a spherical mesh. The support material area around the mesh is computed in *Step 4* and polygons forming the top of the light pipes are computed. The light pipes walls are extruded from the curved surface into the bottom plane in *Step 5* creating areas where support material will be printed. The light pipes are filled with the optical clear material in *Step 6* producing final model that is 3D printed.

Touch Sensing with PAPILLON

The printed light pipes allow bi-directional curved surfaces where the same structures are used both to display an image and measure touch location. We chose to use diffuse IR illumination and camera based sensing, because this allows to preserve the physical decoupling between the interactive touch display and sensing apparatus.

We implemented touch and position sensing by augmenting 3D printed sphere with 8 infrared LEDs with a wavelength of 850 nm (Figure 7). As the user finger is approaching the spherical surface, infrared light bounces from the finger into the light pipes and onto a two-way mirror. A mirror, which is an acrylic sheet coated with aluminum oxide, is 50% transparent passing the light from the projector creating an image on the surface of the sphere. At the same time the mirror reflects IR image from the light pipes onto a PointGrey Flea3 monochrome camera outfitted with 2.1 mm wide angle lens. A Kodak No87 Wratten IR filter removes visible light from the projector and the environment. To track the position of finger the infrared image captured by the camera is filtered, the background is subtracted and resulting image is thresholded to improve the image clarity. The image is then dilated to account for the spacing between printed light pipes, producing contiguous shapes detected with blob detection algorithms (Figure 7).

The resulting design allows us to both display images on the surface of the 3D printed sphere and sense position of human finger touching its surface. This technique is generic and can be extended to any other 3D printed curved display surface of the similar size. As with most diffuse illumination touch displays, ours is designed to detect actual surface contact, it can see the finger about 10mm above the surface.

APPLICATION: INTERACTIVE CHARACTERS

There are multiple applications of 3D printed curved interactive surfaces. We explored applications of PAPILLON for designing highly expressive animated eyes for interactive characters, robots and toys (Figures 8, 9). Our technology has a number of advantage when compared with alternative approaches.

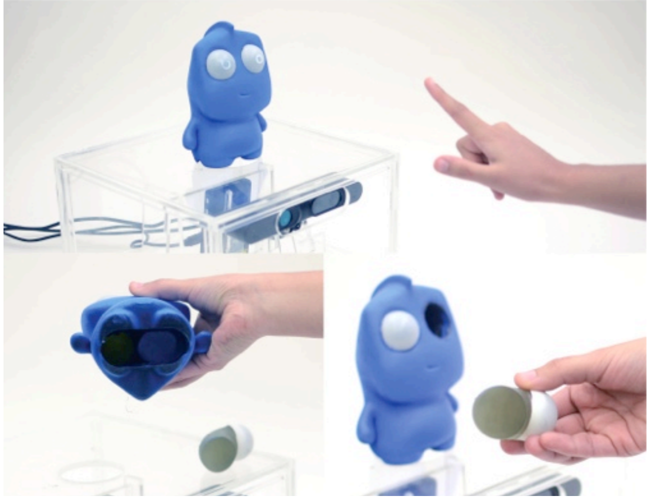

Figure 8. Interactive characters with *PAPILLON*.

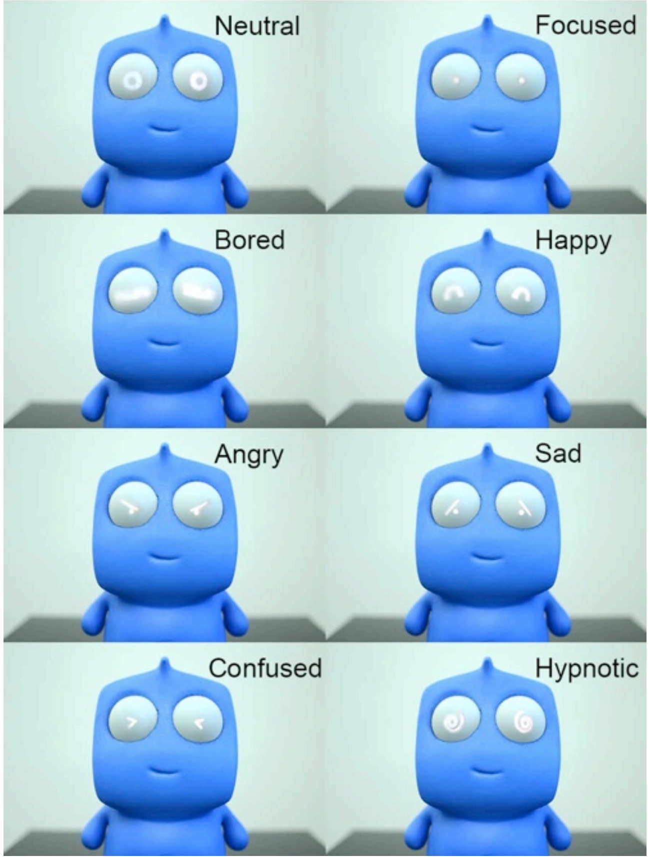

Figure 9. Dynamic animated eyes with PAPILLON.

Arbitrary eye shapes and placements. Our eye elements are digitally designed and 3D printed, therefore, they can take any shape and location that is required by the character. They also extend to characters with a multitude of eyes.

Passive, non-instrumented characters. The characters and toys implemented with *Papillon* technology do not have any interior active electronic elements, moving parts, wires and power requirements. They are completely passive and all the images are projected from the outside into the character (Figure 8) This allows creating engaging, yet easily replaceable and very robust interactive characters.

Rich interactivity. Characters are instrumented with depth camera which tracks presence of the user as well as basic interactions, such as pointing or extending the hand.

Rich communication and expressiveness. Because images are projected into the character's eyes, they can communicate a rich set of emotions and intentions (Figure 8). The expressions that our characters create can not be produces by traditional animatronic technologies.

We evaluated our characters in informal studies with children 6 to 8 years old and the response was extremely positive. Children had no difficulties in recognizing the emotions and "facial expressions" communicated by our characters via animated eyes. They found our characters to be fun and engaging.

CONCLUSIONS

PAPILLON opens new and exciting opportunities in creating novel interactive devices. In particular it allows for the design and exploration of novel form factors for display devices and their applications. This paper establishes basic approaches to designing and developing novel display form factors using a printed optics approach. We hope that it will provide foundation and encourage researchers and practitioners in future experimentation and development and may be applied to a broader range of surface topologies and applications.

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