HoloFlex: A Flexible Holographic Smartphone with Bend Input

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Abstract
We present HoloFlex, a 3D flexible smartphone featuring a lightfield display with 16,640 microlenses. HoloFlex renders "holographic" images providing motion parallax and stereoscopy to multiple users with a resolution of 160x104 pixels, without glasses. Images are rendered into 12-pixel wide circular blocks, each of which displays a fish-eye view of the 3D scene as observed from a particular viewpoint. The lenses distribute each pixel in a direction that preserves the angular information of light rays. Touch input allows for *x,y* input, while bend sensors allow users to control the *z* dimension, by squeezing the display.

Author Keywords
Organic User Interfaces; Lightfield Displays; 3D Input.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous

Introduction
While 3D graphic interfaces have come a long way in the last 50 years, to date much of the 3D content remains rendered as a 2D image on a flat panel display. Lenticular displays offer limited forms of glasses-free horizontal stereoscopy, with some solutions providing limited, one-dimensional motion parallax [10]. Virtual and augmented reality systems, such as the Oculus Rift

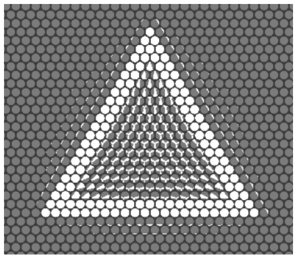

Figure 1: 3D Lightfield rendering of a tetrahedron (inset top-right shows 2D rendition). Note the 12 pixel wide circular blocks rendering views from different camera angles.

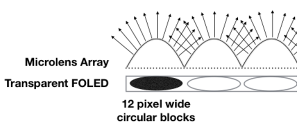

Figure 2: HoloFlex side close-up with 12-pixel wide pixel blocks and half-dome microlens array dispersing light rays.

[11] and the Microsoft HoloLens [9], require headsets and motion tracking to provide immersive 3D imagery. Recently, there has been a renewed interest in 3D displays that do not require glasses, motion tracking or headsets. This research has focused on *lightfield* displays [3,4], which can "holographically" render a 3D scene by preserving all angular information of light rays. Due to their size, lightfield display systems have traditionally been used in desktop applications and, with some exceptions, are generally not suitable for mobile use [8].

In this paper, we present HoloFlex, a glasses-free 3D smartphone featuring a flexible thin-film lightfield display. The 3D image is rendered on the display by a ray-tracing algorithm that simulates a hexagonal array of 160*x*104 virtual fisheye cameras (see Fig. 1). An array of 16,640 microscopic half-dome fisheye lenses distributes the rays of each virtual camera horizontally and vertically back into the eyes of the user, reconstructing the 3D scene (see Fig. 2). HoloFlex uses a Flexible Organic Light Emitting Diode (FOLED) display with 403 DPI resolution to render the lightfield. It features a touch screen for *x,y* input and bend gestures for *z* input.

Related Work

Kim et al. [6] exploited color and angular limitations of LCD displays to show two independent images at two different viewing angles. This process allowed the user to protect private information from bystanders, and could also generate stereo 3D images. Another type of multi-view display relies on head tracking to deliver motion parallax to a single user. Benko et al. [1] demonstrated a tabletop prototype that allowed the user to interact with 3D objects, with applications in gaming, 3D modeling and teleconferencing. Lightfield displays, however, are different in that they fully emulate the actual field-like propagation of light. Thus, lightfields exhibit same properties as holograms in that they do not require special glasses or head tracking for stereoscopy or motion parallax. Hirsch et al. [5] combined a large passive lenticular projection screen with essentially two high-speed projectors to create a ligthfield display. Their system was used mainly for producing 3D imagery with no specific input method. Peng et al. [12] used a lightfield display based on an array of projectors combined with Kinect-based input for teleconferencing purposes. Hirsch et al. [4] created a lightfield capturing 2D display to recognize 3D gestures. They employed an LCD doubling as a camera aperture array to optical sensors located behind it. Hirsch et al. [3] implemented a real-time display that reacts to incident light sources. Users can use colored light sources as input controls for applications such as illuminating virtual 3D objects. Tompkin et al. [13] developed a lightfield painting system, which both captures (from a light pen) and displays a lightfield. Most of the aforementioned lightfield display implementations require the use of bulky equipment, making them impractical for mobile use.

Bend Gestures for 3D input

A persistent issue with 3D displays is devising a natural form of input that integrates the *x,y* with *z* axis control. Lahey et al.'s PaperPhone [7] featured a thin-film electrophoretic screen with a flexible circuit board capable of sensing screen deformations. Bend gestures were used to navigate and zoom in/out of items on the display. Since bend gestures seem well-suited for *z*-input [2], we incorporated a bend sensor into our design of a flexible lightfield display.

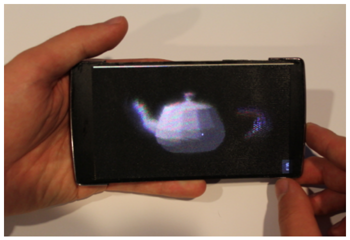

Figure 3. HoloFlex flexible lightfield smartphone. Bend input is used to translate objects along the z axis.

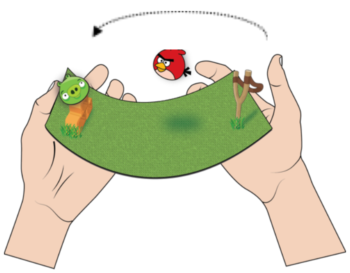

Figure 4: Holographic physical gaming application. Bend input is used to propel the character towards the target. As the character moves, it appears to jump out of the holographic display.

Implementation

Figure 3 shows the HoloFlex prototype. The first layer is a 3D printed flexible lens array consisting of 16,640 half-dome shaped droplets in a 160 *x* 104 hexagonal matrix. Each droplet is 0.375 mm in radius, and is surrounded by a black circular mask. The mask limits the bleed from unused pixels, effectively separating lightfield pixel blocks from one another. The touch input layer consists of a flexible capacitive touch film by LG Display that senses *x,y* touch with a resolution of 1920 *x* 1080 pixels. The display layer consists of a 121 x 68 mm LG Display FOLED with a resolution of 1920 *x* 1080 pixels (403 dpi). HoloFlex features one bidirectional 2" FlexPoint bend sensor placed horizontally behind the center of the display. The bend sensor is connected to an RFduino chip with Bluetooth hardware. RFduino Library 2.3.1 allows communication of bend sensor values to the Android board over Bluetooth. The final layer consists of a 66 *x* 50 mm Android circuit board with a 1.5 GHz Qualcomm Snapdragon 810 processor and 2 GB of memory. The board runs Android 5.1 and includes an Adreno 430 GPU supporting OpenGL 3.1. The circuit board was placed such that it forms a rigid handle on the left back of the HoloFlex device. The handle allows users to comfortably squeeze the device one-handedly.

Rendering Algorithm

In HoloFlex, each pixel block rendered on the lightfield display consists of an ~80 pixel circular image of the entire scene from a particular virtual camera position along the *x,y* plane (see Figure 1). The field of view of each virtual camera was fixed by the optical properties of the microlenses to approximately 35 degrees. The scene is rendered using a ray-tracing algorithm running on the GPU of the phone. We implemented a custom OpenGL fragment shader in GLSL ES 3.0 for real-time rendering by the phone's on-board graphics chip. The generated scene and touch input are managed by a Unity 5.1.2 application.

Application Scenarios

We developed a number of scenarios that highlight the new functionality provided by our HoloFlex prototype.

Holographic Editing of a 3D Print Model

Our first application demonstrates the use of bend gestures for Z-Input to facilitate the editing of 3D models, for example, for 3D printing tasks. Here, *x,y* positioning of a 3D element is implemented using drag and drop on the touch screen. At the same time, flexing the screen at the middle, by squeezing it with the non-dominant hand [2], moves the selected element in the *z* dimension. An element's *x,y,z* orientation can be controlled with the prototype's inertial sensors (IMU). By bending the display into a concave shape, multiple users can examine a 3D model simultaneously from different points of view (Fig. 3).

Holographic Physical Gaming

Our second application is a holographic game (Figure 4). We chose to develop a 3D version of the Angry Birds game in Unity. Rather than using touch input, users can bend the side of the display to pull the elastic rubber band that propels the bird. When the user releases the display bend, the velocity of the spring back action in the display is sensed by the bend sensor, and is used as the bird's velocity. This provides the user with real passive haptic feedback that represents the tension in the rubber band. When the bird flies across the screen, it literally pops out of the screen in the *z* dimension.

Conclusions

We presented HoloFlex, a 3D flexible smartphone featuring a lightfield display with 16,640 microlenses. HoloFlex renders "holographic" images featuring motion parallax and stereoscopy to multiple users with a resolution of 160x104 pixels, without glasses or head tracking. Images are rendered into 12-pixel wide circular blocks, each of which displays a full view of the 3D scene as observed from a particular viewpoint. The lenses distribute light from each pixel in a direction that physically recreates the viewpoints. Altogether, the array of viewpoints composes a lightfield image of the scene. Bend input allows users to move 3D objects in the *z* dimension by squeezing the display.

Acknowledgements

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