Portallax: Bringing 3D Displays Capabilities to Handhelds

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ABSTRACT

We present Portallax, a clip-on technology to retrofit mobile devices with 3D display capabilities. Available technologies (e.g. Nintendo 3DS or LG Optimus) and clip-on solutions (e.g. 3DeeSlide and Grilli3D) force users to have a fixed head and device positions. This is contradictory to the nature of a mobile scenario, and limits the usage of interaction techniques such as tilting the device to control a game. Portallax uses an actuated parallax barrier and face tracking to realign the barrier's position to the user's position. This allows us to provide stereo, motion parallax and perspective correction cues in 60 degrees in front of the device. Our optimized design of the barrier minimizes colour distortion, maximizes resolution and produces bigger *view-zones*, which support ~81% of adults' interpupillary distances and allow eye tracking implemented with the front camera. We present a reference implementation, evaluate its key features and provide example applications illustrating the potential of Portallax.

Author Keywords

Mobile 3D; Clip-on; Autostereoscopic; parallax barrier; handheld device; face-tracking.

ACM Classification Keywords

H.5.2 [Information interfaces and presentation]: User Interfaces - Graphical user interfaces;

INTRODUCTION

3D stereoscopic systems and content have attracted the interest of users throughout the years. After Avatar (2009), twenty eight 3D titles were released in 2010, thirty six in 2011 and over forty in 2012 and 2013 [4]. Multiuser 3D TVs technologies have also been proposed [15], and glasses-free TVs, like Toshiba 55ZL2, reached the market in 2012.

The market of mobile devices joined this 3D trend a few years ago. Sharp mova SH251iS, the first stereo 3D enabled mobile phone, was released in 2002 and since 2010 we have witnessed a new generation of 3D enabled handheld devices, with the HTC Evo 3D, Sharp Lynx 3D, Samsung SCH-B710 or LG Optimus as just some of the latest examples. Clip-on solutions, like 3DeeSlide [1] or Grilli3D [3] allow retrofitting other non-3D devices with similar 3D capabilities.

Figure 1. Portallax is the first clip-on technology that provides 3D visualization even when users move their head or their device. It uses an actuated parallax barrier, providing stereoscopy, motion parallax and perspective correction through face tracking

With the arrival of these mobile 3D display technologies, the stage seemed to be ready to allow mobile devices fully supporting 3D experiences. The graphical capabilities of mobile devices allow compelling scenes, as demonstrated by the ever growing mobile gaming industry. Interesting usage scenarios have been identified (e.g. stereo games [30], mobile 3D TV [20] and user interfaces [16]). The capability of these devices to process 3D video contents has also been demonstrated[37]. Finally, 3D gestural input can be used to interact with the 3D contents shown on these devices, either using magnets attached to the users' hands and fingers [17, 22, 23] or even with the bare hands[6, 35]. However, the acceptance of these stereo 3D mobile devices has been low. According to *M&M* only 16 million of the 1.1 billion smart phones sold in 2013 were 3D enabled [2].

The exact reason behind the slow uptake is not fully clear, but we believe that the limitations of current mobile 3D display technologies are an important factor. Existing technologies rely on static parallax barriers or lenticular arrays, which show a correct 3D effect only at a fixed

Figure 2. : Nintendo 3DS (A), an example of commercially available mobile 3D device, features a static parallax barrier. Clip-on solutions like Grilli3D (B) or 3DeeSlide (C) use static parallax barriers or static lenticular arrays.

position in front of the screen (*view-zone)*. In a mobile scenario, however, it is likely that users will move their head, or more importantly their devices. Such a situation frequently occurs while playing games, either because the interaction involves tilting the device to control an avatar, or simply because users are too absorbed in their action and move the device to try to influence an action. In this context, if the user moves out of the 'sweet spot', the stereoscopic effect breaks. Also, *motion parallax* which is a strong depth cue for perceiving 3D content [19] is not available. Many techniques relevant for 3D navigation (e.g. gaze steering [5]) or 3D manipulation using touch screens [14, 28] also rely on the ability of the users to move their heads, and thus cannot be supported by current mobile 3D technologies.

Finding an alternative mobile 3D display technology that allows users to move and is also well suited for handheld use is difficult. Such technology should avoid instrumenting the user (e.g. no glasses) and adapt to a wide range of users (e.g. variable interpupillary distance –IPD). It should rely on self-contained computing and fit within a thin form factor. It cannot interfere with the typical use of conventional 2D applications, and should be cheap to produce, to qualify as a successful clip-on solution.

We explore the existing range of mobile 3D display technologies, looking for an alternative that complies with the stated requirements. We then present Portallax (Figure 1), a *clip-on* solution that uses a mechanically actuated parallax barrier and face tracking to support a working volume of 60°. The 3D position of the observer's eyes is used to realign the barrier in real time, and provide perspective correction. Given that the user can move in front of the display, motion parallax as well as 3D interaction techniques can be supported. We provide a proof of concept implementation which achieves all this with just clip-on hardware made from off-the-shelf components and without compromising the interactive capabilities of the device. Portallax implements an improved version of parallax barrier which increases the size of the *view-zones*, eliminates *hue shift* and has better effective resolution than classical parallax barriers.

We present the design of the device as well as example applications that illustrate its key capabilities. We then show the results of a quantitative evaluation of its most relevant features: working volume, tracking response and resilience to *ghosting*. Finally, we provide a discussion on the capabilities and limitations of our approach, as well as of improvement and the potential of this type of devices.

PORTALLAX: GOALS AND DESIGN

The current paper focuses on the possibility to retrofit existing devices with 3D display capabilities. Thus we consider three factors to guide our design. The first one was to overcome the limitations in existing approaches. Secondly, the context of use of these devices was also considered, based on the observations reported by Jumisko-Pyykkö [20]. Finally, technical aspects, like the computing capabilities of current mobile devices or costs have been considered. The following set of goals was established to guide the design of Portallax:

- *Support for a big working volume*: As opposed to existing mobile 3D solutions, the working volume of the clip-on should be as big as possible. This feature facilitates its usage, as users do not need to align and stay at fixed positions to see the effect. Freedom of movement within a bigger volume adapts better to the contexts of use (e.g. public transport, walking through cities) described in [20]. Interaction techniques relying on accelerometers [30] or user head movements [5, 14, 28] can be used together with the 3D effect.
- *Support for additional depth perception cues*: The clip-on should provide binocular disparity (*stereopsis*) and also support *motion parallax* with *perspective correction*. These cues are known to greatly enhance the perception of 3D content [19]. Eye tracking within the working volume might be required to provide perspective correction when a limited number of views are generated.
- *Support seamless integration:* Jumisko-Pyykkö [20] suggests that 3D contents should be available for short periods. Thus the attachment should allow seamless transitions between stereo 3D and 2D applications. It should not limit the existing capabilities of the device (e.g. access to the touch screen) or the way it is used.
- *Self-contained operation:* A wide variety of contexts of use are envisioned (indoor, outdoor, cafes, parks, etc). In order to support the contexts of use envisioned, the clip-

on attachment should not require extra hardware on the user (e.g. glasses) or require connections to non portable external devices (e.g. computers, fixed tracking systems).

- *Form factor and quality considerations:* To be really useful, the design should add minimally to the form factor of mobile devices. Being a clip-on solution, the overall cost of the elements used and the simplicity to mount it become critical factors.

ANALYSIS OF MOBILE 3D DISPLAY TECHNOLOGIES

One of the most critical factors for the design of Portallax is the choice of the appropriate 3D display technology. Most mobile 3D displays technologies are *autostereoscopic* (the user does not need any eyewear) and also are *multiview* displays (deliver several views to different *view-zone*s). The most common approaches used to achieve these capabilities are parallax barriers [10], lenticular arrays [27] and directional backlighting [38].

Each of these three approaches has been applied to the mobile context. Consoles like Nintendo 3DS (Figure 2 A); mobile devices like HTC Evo 3D, Sharp Lynx 3D, Samsung SCH-B710 or LG Optimus; and even cameras, like Fuji FinePix, use a fixed two view parallax barrier. A dedicated LC panel displays or hides the barrier allowing the device to switch between 2D and 3D modes. Flack et al. [13] proposed a mobile device that allows this same feature for a lenticular array. 3M manufactures *lightguide plus retardation* film, which transforms mobile devices' backlighting making the pixels of the TFT only visible from certain positions. Clip-on solutions have also been proposed using both parallax barriers (Grilli3D [3] in Figure 2 B) and lenticular arrays (3DeeSlide [1] in Figure 2 C). They can be attached to the mobile device while still being able to use its multitouch screen.

In all the previous approaches, the barrier is static. They generate two fixed *view-zones* and, thus, the stereo effect only works at a fixed position in front of the display.

Other multiview displays use information about the position of the user to support a bigger working volume. Woodgate et al. [38] and Dodgson [7] propose displays with three or four *view-zone*s, each smaller than a fraction of the user's interpupillary distance (IPD). The positions of the user's eyes are detected and the contents (left eye or right eye views) are swapped to the appropriate *view-zones* for the user to perceive correct 3D imagery. The NEC HxDP display [34] uses this technique, adapting it for a mobile device and lenticular arrays.

However, this technique also imposes some limitations. For an average IPD distance of 63 mm [8], the four *view-zones* would measure 63/4 ~ 16 mm. The tracking system would need to support an accuracy of 8 mm, which is not achievable with the front facing camera found in most devices. Creating these *view-zones* might require additional spacing between the display and the parallax barrier (e.g. up to 5 mm, for a Galaxy Tab like the one we use in our prototype), which adds to the form factor and would prevent the usage of the touch screen. Finally, using four views the resolution for each eye would be, at best, 25% of the original screen resolution.

Instead of swapping, other approaches physically move the *view-zones* according to the user position. This can be done by mechanically rearranging parts of the display [9, 11, 18, 38], but other approaches have also been proposed.

The Varrier [33] and Dynallax [32] use passive barriers, but they rearrange the image at a subpixel level, aligning it to the user's eyes. This requires a rendering overhead of, at least, three rendering passes per eye (excessive in a mobile context) and only provide an effective resolution of 25% for each eye. Their working volume is also small if the user is located close to the display, as would be the case with a handheld device.

Perlin et al.'s autostereoscopic display [31] and MUSTARD [21] use an LC arrangement that allows them to rearrange the position of the parallax barrier and random hole mask respectively, to the current position of the observer. However, current mobile devices do not support synchronized dual graphical outputs (similar to NVIDIA Quadro GSync cards), which are required to operate these displays. The additional LC panel would also require an external power source, occlude the touch screen and drive up the cost of the implementation, which should be ideally low for a clip-on solution.

Following a different approach, non-tracked multiview displays create a large number of views of the 3D imagery. This allows observers to see correct 3D independently of their position, does not require tracking and allows for multiuser operation. However the real-time generation of all the views might be problematic and the resolution of each view is reduced (i.e. display resolution divided by number of views). Recently Fattal et al. [12] reported a backlighting technology capable of creating up to 64 views in a compact form factor. Lanman et al. introduced a new approach that uses stacked LC panels to create an approximation of the constrained 4D lightfield of a 3D scene [24, 25]. This allows multiple full resolution views around the display and the authors propose it as a valid solution for mobile devices. These solutions open interesting opportunities for future mobile devices, but current devices do not have the resolution or the computing power required to operate these displays or create 3D imagery in real time.

Instead, Portallax uses a two view parallax barrier which is mechanically actuated using a microcontroller and two servo motors, all powered through the USB connection. *View-zones* are aligned to the position of the observer using eye tracking and the device's onboard camera. This reduces the costs and power requirements of the solution.

Portallax relies on a novel approach for barrier design that provides wider *view-zones*, to cope with the relatively low

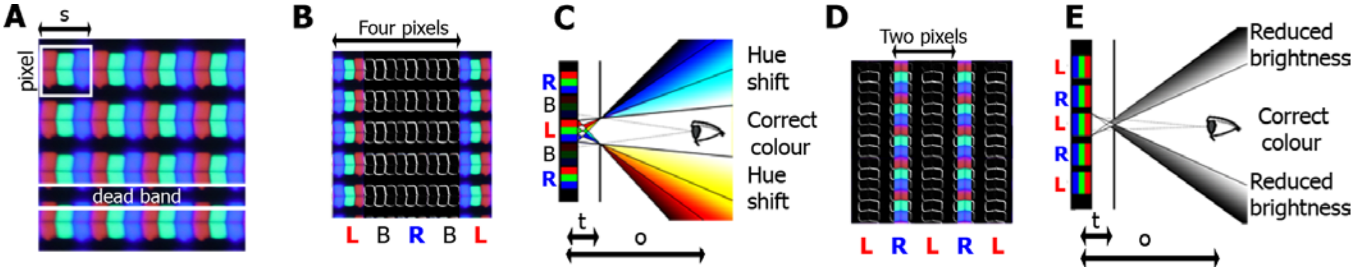

Figure 3. Parallax Barrier Configuration: (A) Microscope photo of panel (B) Classical barrier setup resulting in (C) *hue shift*, small focal regions and four pixel patterns (reduced resolution). (D,E) The Portallax approach uses a two-pixel pattern and has increased resolution and visibility.

precision of our tracking system. It also reduces *hue shift* and provides 50% effective resolution for each eye, maximizing image quality.

Portallax's Parallax Barrier

In a standard LCD panel, the pixel is made up of red, green and blue subpixels arranged in a horizontal row (Figure 3 A). The rows are separated by gaps (~25% of pixel pitch '*s*') where the ITO circuitry resides (*dead bands*). Most parallax barriers (Figure 3 B) use vertical slits (running perpendicular to the pixel rows) or slanted slits (~30% from the vertical [33]). These arrangements have beneficial features, such as support for subpixel algorithms or alleviating Moiré effects. However, as the user moves to the sides, red and blue subpixels get partially occluded (see Figure 3 C), varying their relative contribution and distorting the colour perceived (*hue shift).*

To compensate for this, slit width can be made equal to or greater than the width of a pixel. Due to this, the neighbouring pixels become unintentionally visible, leading to *ghosting*. *Ghosting* can be minimized by blanking out the neighbouring pixels (usually called *pixel guardbands*). The resulting arrangement is the classical barrier design with repeating blocks four pixels wide [32, 33]: one pixel each for left (L) and right (R) eyes interleaved with one pixel wide *pixel guardbands* (B). Note the L-B-R-B pattern in Figures 3 B and 3 C. The effective resolution is 25% of the horizontal display resolution for each eye. Another important parameter is the barrier's *duty cycle*, that is, the percentage of the barrier pattern that the slit occupies (*slit/(slit+barrier*)). The typical *duty cycle* is 25% and can go up to 50% to get brighter images (but smaller *view-zones*).

Portallax manages to avoid *hue shift* and allows a higher resolution per eye by using a novel barrier design based on three heuristic features: *rotated barrier*, *narrower slit* size and *hardware guardbands.* These are described next.

Rotated barrier to avoid hue shift

Portallax uses a barrier rotated by 90° to the pixel rows (see Figure 3 D). The rotated barrier reduces the *hue shift* as all three subpixels are equivalently and simultaneously occluded by the barrier. The proportion to the *view-zone*s free of *hue shift* is bigger than before and this effect is mostly replaced by a linear loss of brightness at the boundaries of the *view-zones* (see Figure 3 E).

Narrower slits to increase resolution

Unlike classic barriers, our slits are narrower than one pixel ($slit<s\cdot(o-t)/o$). Neighbouring pixels are not visible through these slits. Thus Portallax eliminates *pixel guardbands* and uses a pattern of two pixels (one for each eye) instead of the four pixel pattern in classical barriers. Note the L-R pattern in Figure 3 D and 3 E. Portallax thus delivers 50% of the display's resolution to each eye, instead of the usual 25%.

Hardware guardbands to reduce ghosting

Portallax also makes use of the *dead band* (shown in Figure 3 A) to further reduce *ghosting*. The *dead band* acts as an implicit *hardware guardband* that prevents *ghosting* when the user reaches the limits of the *view-zone.* At the same time, these are not *pixel guardbands*, so the full resolution of the LC panel remains usable. The *hardware guardbands* can also be used to help optimize the width of the *view-zones* as explained in the next section.

Slit size computations

A large *view-zone* is vital for the success of Portallax. In an ideal classical barrier (Figure 4 A), the size of the *view-zones* '$\omega(o)$' at the optimal viewing distance '*o*' is, at best, as wide as the conflict region '*c(o)*' (region where both R and L views are visible). This ratio is even smaller as the observer moves forward or backwards.

Our barriers minimize the width of the conflict zone. The relation between the size of the *view-zone* and conflict zone in Portallax can be described by:

$$\omega(o) = (o - f) \cdot \tan\alpha;\ c(o) = (o - t) \cdot \tan\beta - \omega(o) \qquad \text{Eq. 1.}$$

For e.g., at o = 350 mm, a comparable classical barrier will have $\omega(o) = c(o) = 36.79$ mm. Our barrier, using a typical duty cycle of 25%, results in $\omega(o) = 55.44$ mm and $c(o) = 18.32$ mm (Figure 4 B). The third arrangement (see Figure 4 C) shows a barrier where the slit is as big as the *hardware guardband*, resulting in optimal regions of $\omega(o) = 73.7$ mm and constant-size conflict regions of $c(o) = 0.04$ mm.

Using an LC panel with *hardware guardbands* as big as pixels (Figure 4 D) would produce the best brightness (33% *duty cycle*) and constant size conflict regions (similar to

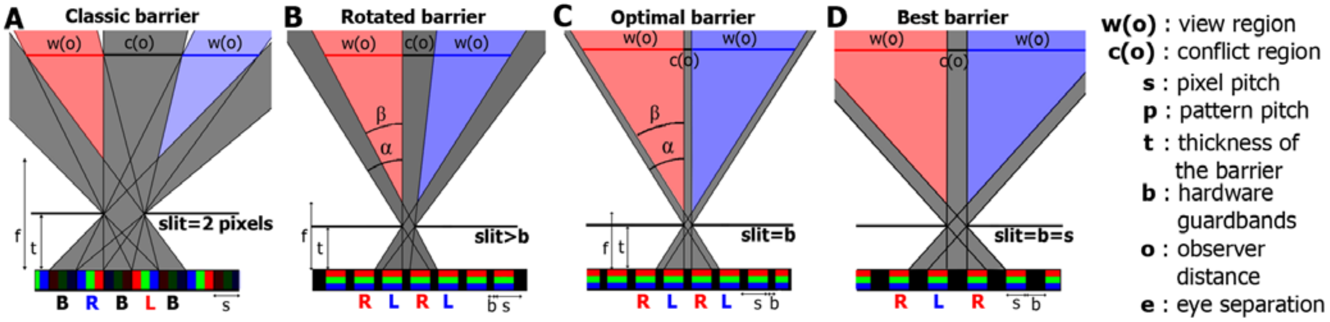

Figure 4. Comparison focal region sizes: (A) Classical parallax barrier. Example Portallax barriers with varying slit sizes (B) slit > guardband (C) slit = guardband and (D) a specially manufactured panel with *hardware guardbands* of the size of a pixel.

Figure 3 C). This arrangement is beyond the scope of this paper as it requires changes at LC fabrication level.

Brightness v/s accuracy trade-off

The previous section describes how the slit size can be used to minimize the conflict zone. However, at the same time, the slit size affects the brightness too. A wider slit (as in Figure 4 B) will produce brighter images, but the size of the *view-zone*s reduces proportionally. A narrower slit (equalling width of the *dead bands*, as in Figure 4 C) produces wider *view-zone*s, but we also see reduction in brightness.

The choice of the appropriate size is actually driven by a third factor: the quality of the tracking technology available. The barrier needs to be repositioned to align the *view-zone*s to the current position of the user's eyes. Errors in registration of the position of the user's eyes will result in misalignments of the barrier, which can break the stereo effect. Thus, the error of the tracking system must be smaller than that allowed by the size of the *view-zone*s.

While it can be hard to eliminate the sources of error (tracking, actuation, etc.) it is possible to evaluate these, and select a slit size, which is as bright as possible, but at the same time produces *view-zone*s wide enough to deal with tracking errors. Our implementation of Portallax's barrier takes this into account as described below.

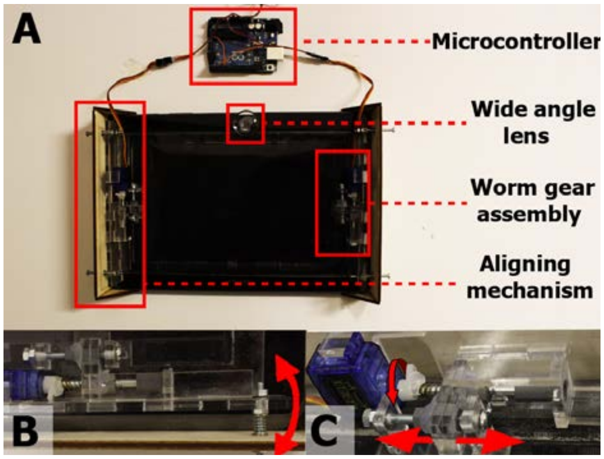

Figure 5. (A) Elements in Portallax. Details of the aligning mechanism (B) and worm gear assembly (C).

IMPLEMENTATION OF PORTALLAX

We provide a reference implementation of Portallax for a Samsung Galaxy Tab 10.1 as shown in Figure 5 A. Additional hardware consisted of the actuation assembly driving the parallax barrier. The parallax barrier was printed on a transparency, to allow *multitouch gestures* to work through it. A mounting frame allows us to fix and align the barrier to the screen (See Figure 5 B). Once installed, no Moiré effects are observed. During operation, the screen is displaced sideways using two servos and a worm gear coupler (Figure 5 C).

An Arduino UNO microcontroller is used to communicate with the device and operate the servos. This additional hardware derives its power from the USB port on the tablet allowing the device to be fully self-contained. One 25 mm off-the-shelf plano-concave lens is included to increase the field of view of the front camera. The current prototype supports a working volume of ~60°, with an optimal observer distance $o=350 \pm 100$ *mm* and an IPD range $e=63 \pm 5$ *mm*, which fits approximately the *~81%* of the adult population [8].

Barrier specifications

The barrier is designed to conform to the working volume we desired to achieve. ($o=350 \pm 100$ *mm*, *60°*). Based on the thickness of the display ($t=0.8$ *mm*), its pixel pitch ($s=0.169$ *mm*) and size of the *hardware guardband* ($b=0.042$ *mm*). The pattern pitch '*p*' (size of one slit and one barrier band) is $2 \cdot s \cdot (o - t) / o = 0.337$ *mm* and its *duty cycle* is *18.75%*. This duty cycle complies with the error produced by our tracking system (*26.4 mm*, as described later) and maximizes brightness. The resulting barrier creates *view-zone*s of up to *64.51 mm*, with conflict zones of 9.25 mm. The resulting tolerance to tracking errors is $\mathcal{E} = (63 - 9.25)/2 = 26.8$ *mm*.

This barrier is the best approximation that our printer (1200 dpi) can provide to the optimum slit size. Error tolerance of *26.4 mm* would require a duty cycle of *19.38%*.

Figure 6. Two examples illustrate key features: (A-C) Users can interact with 2D and 3D contents in a medical application. (D and E) The jet application uses the position of the user relative to the screen to control the direction and speed of the fighter.

Actuation and alignment of the barrier

According to the thickness of the display (t = 0.8 mm) and the angle covered by our working volume (*FOV*), the barrier must be displaced up to $2 \cdot t \cdot tan(FOV/2) = 0.924\ mm$.

We use a paired worm gear assembly [29] powered by two servos to perform this actuation (Figure 5 C). This speed reduction coupling ensures high precision control over the displacements of the barrier. The coupling maps the 256 steps of the servo to the *0.924 mm* we need to displace the screen, achieving a resolution of *0.004 ± 0.002 mm*. The misalignment due to this error for an ideal observer (located at *350 mm*) is *1.75 mm*, which is considerably smaller than the error introduced by the tracking system.

The coupling increments the power of the servo proportionally (i.e. our servos' torque of *1.5 Kg/cm*, corresponds to *1.5 Kg/0.924 mm ~1600Kg*). It is also a non reversible coupling, assuring that users' displacements of the screen (e.g. when using finger gestures) will not affect/destroy the servo.

The servo features a rotation speed of 500 degrees per second. This would correspond to a user moving from one end of the working volume to the opposite (*350mm*) in *340 ms* (i.e. *1.03 m/s* observer speed). Maximum observer speed is mostly constrained by the frame rate of the front camera (up to 15 fps in our device and most current devices), rather than to the capabilities of our clip-on solution.

Tracking Algorithm

Portallax uses the front camera to perform an approximate 3D tracking of the user's eyes. This information is used to realign the position of the barrier (to support *stereopsis*) and to correct the perspective according to the relative position of the observer to the screen (to support *motion parallax*). The camera resolution used is 640×480 and covers a volume of up to 60° horizontally in front of the screen (once the wide angle lens is added). It provides up to 15 fps, but its frame rate can decrease in poor lighting conditions.

The tracking algorithm is an OpenCV implementation of the face tracking algorithm by Viola and Jones [36]. Template matching is used to detect the pupils. The 3D position is then estimated using an assumed eye separation of 63 mm and that the user is looking head-on at the display. An α-β filter is used to smooth the measures returned by the algorithm and forward predict the current location of the observer.

Rendering algorithm

Portallax uses a modified version of Rajawali (https://github.com/MasDennis/Rajawali) to generate 3D graphics. We use the stencil buffer to interleave odd and even columns in the display for the left and right eyes, in a similar way to how interlaced stereo was generated in old HMDs. Each frame is rendered twice, once from the point of view of each eye. Off-axis projection of the frustum, according to the relative position of the eye to the screen is performed to correct the perspective.

This implementation incurs the minimum overhead possible for a stereo rendering. The stencil buffer does not need to be recomputed, as pixel columns are always assigned to the same eye, so only the left and right images need to be recomputed.

EXAMPLE APPLICATIONS

Portallax opens an exciting spectrum of new interaction possibilities. Its support for additional stereo cues, allows the replication/adaptation of techniques proposed in the context of 3D user interfaces and tabletop 3D interaction [5, 14, 28]. However, its mobile nature allows these techniques to be applied in novel contexts, like augmented reality. Its ability to interweave these 3D applications with the applications users use in their day to day life creates a very interesting design space.

We feel we cannot do justice to exploring the complexity of this design space in the current paper. The applications presented are thus only intended to illustrate what we consider to be two key aspects: The possibility to seamlessly switch between 2D and stereo 3D tasks and the support for interaction techniques that allow the user to move in front of the device.

The first example replicates a medical application to visualize annotated 2D and 3D information, easily switching among both types of contexts (Figure 6 A-C). The users can browse 2D reports of their patients using

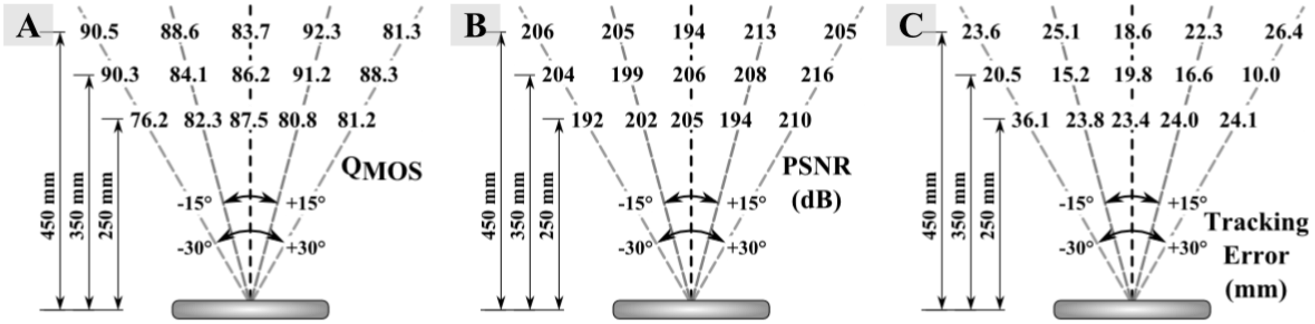

Figure 7. Results table: (A) QMOS and (B) PSNR were used to evaluate the presence of ghosting in the system. (C) The tracking error was also evaluated, confirming that it stays within the margins allowed by our barrier.

conventional gestures (e.g. swipe to scroll, two finger gestures to zoom in and out). 3D models of the anatomy of their patient are embedded in these reports, which the user can visualize by clicking them. Finger touches translate the 3D model and two finger gestures can be used to scale and rotate it. This 3D model contains annotated information, that can be clicked to reveal other relevant pieces of information i.e. other 2D content like reports or 3D models.

The second application is a flight simulation game (Figure 6 D, E). The control of the jet relies mostly on the way the user moves relative to the tablet. The observer distance (Z coordinate) is used to control acceleration. If the user moves further than 40 cm, the velocity is increased, if he approaches closer than 30 cm, the speed of the jet is reduced. This way, kinaesthetic cues are used alongside 3D cues to improve the player's sense of immersion. The roll and pitch of the aircraft is determined by the X and Y position of the user’s head. This allows the user to control the direction of the jet in two different ways, by tilting the display or by moving himself. In this last case the tablet serves as a window, revealing the parts of the 3D world the aircraft flies in.

In both examples stereo images, corrected perspective and motion parallax are provided all the time. Objects are placed behind the screen for visual comfort.

EVALUATION OF THE DISPLAY

We performed a quantitative evaluation of the view quality of the prototype to determine how well Portallax fulfils its design requirements. Specifically we measured *ghosting* to measure the quality of the stereo effect within the working volume and the accuracy of the eye tracking algorithm.

Ghosting

We placed a camera behind the right eye of a dummy human face. The face was positioned such that the right eye would be at distances of 250, 350 and 450 mm from the screen (minimum, optimum and maximum distances of our working volume). At each of these, the position was further offset horizontally to emulate 30°, 15°, 0°, -15° and -30° positions. The resulting positions mimicked a user tilting the display and moving in front of it. At each position, six photographs were captured. The first was used as a reference image with right eye seeing a solid blue rectangle and the left eye view turned off. The other five test images were taken with the same right eye view and a solid green rectangle as the left eye view. We also recorded the eye position as detected by the eye tracker every time.

The view quality was analysed using HDR-VDP2 [26] using their reference implementation to compute a Q_{MOS} score ([0→100], 100 is best). This metric measures perceivable differences for an average human observer. PSNR value was also computed, to measure objective interference due to ghosting. The results are shown in Figure 7 A, B. Q_{MOS} scores had a mean value of 85.64 (σ=4.68), indicating that the *ghosting* is minimal and not easily visible to the human eye. PSNR, with an average value of 203.97 dB (σ=6.79), also aligns with these results. Both results confirm our informal observations that no noticeable *ghosting* is present.

Tracking accuracy

As discussed previously, the precision of the tracking system affects the design of the barrier. More accurate tracking allows wider slits, which result in smaller *view-zone*s but also a brighter image. We evaluated the accuracy of our tracking algorithm twice, once to design our barrier and a second time to validate our design. We only report the results from the second study, as they are similar to the ones from the first study.

The values returned by our tracking algorithm were recorded while taking the pictures for the *ghosting* evaluation. As shown in Figure 7 C, the tracking error (distance to actual position) is always within the error range of our barrier. The only exception is the set of measures at the left extreme angle, at 250mm. The fact the Q_{MOS} and PSNR also reveal lower scores at this position pushes us to believe that there could be an alignment error on the wide angle lens of our device. This could cause errors in our tracking system, which in turn would cause the barrier to be incorrectly aligned, producing more *ghosting*

DISCUSSION

Limitations

The demonstrated prototype is not without limitations. The usage of off-the-shelf elements adds too much to the form factor of the tablet. The case used to mount and align the clip-on to the tablet is precise but rudimentary. The case was, however, a matter of convenience. A finished product should take care of these elements. Protective cases should be produced using integrated elements (i.e. to add minimally to the form factor) and adapted to the size and panel features of each device. Aesthetic aspects should also be considered. We found that the noise produced by the servos could be distracting. Lubricant and a strong fixation to the case helped reduce their noise to a minimum. Usage of better quality servos would reduce noise eve further, but increase the cost of the solution.

The possible interference of the attachment with other applications also requires consideration. During our development, we realized that the minimum font size had to be 3mm (8.5 pt) to be readable. The wide FOV lens could also affect the experience of the user with videoconference applications such as Skype. The overall brightness of the device is diminished, as a result of the barrier. The orientation of the barrier limits the stereoscopic operation to the portrait mode of the device. This may be useful for applications like 3D video conferencing but not for others. Also the frame rate of the camera decreases in poor lighting conditions. This affects the tracking speed thus slowing down the responsiveness of the barrier.

The impact that these limitations have on the user experience is beyond the scope of this paper and could be dealt with in future work.

Going beyond Portallax

We firmly believe the design of Portallax provides a clip-on solution that could benefit a huge number of mobile devices. However during our implementations, we did note that certain small design changes in the manufacturing of the devices could prepare them to work nicely with this kind of *clip-on* solutions. For example, if it was possible to pre-select the pixel pitch (s), the thickness of the display (t), the *hardware guardband* size (b), the device would have a pre-optimized *view-zone*s. Ideally, *view-zone*s of 75 mm can adapt to the vast majority of adults [8]. Products designed for children could equally be adjusted. Likewise, a *hardware guardband* of the same size as the pixels would allow for barriers that maximize brightness and size of *view-zone*s, as illustrated in Figure 4 D.

Increasing the frame rate of the front cameras, would improve the tracking quality (i.e. no blurring due to high speed head movements). This could lead to less restrictive barriers (wider slits) and brighter images. In addition to this, removing the IR filter from the front camera would enable the use of IR illumination to enhance the visibility of the user’s pupils (i.e. better accuracy) and maintaining a high frame rate even in dark environments.

CONCLUSIONS AND FUTURE WORK

The current paper focuses on the engineering aspects related to Portallax. As already mentioned, aspects related to the usability and best application scenarios for this technology remain as potential lines of future work. Portallax enables a design space that mixes elements from 3D user interfaces, interactive surfaces and mobile devices. The techniques for 3D manipulation with tabletop surfaces should be revisited for this context of use. The smaller size of the screen and the fact that users need to hold the device at least with one hand, can affect their validity. Current studies on mobile 3D gaming might also need revalidation, as the additional stereo cues and interaction techniques offer new possibilities to the user experience.

This paper has presented Portallax, an improved version of an actuated parallax barrier that converts an existing handheld device into a stereoscopic 3D enabled device without limiting the device's interactive capabilities. Portallax provides and optimized design of parallax barriers, alleviating traditional issues. *Ghosting* and *hue shift* are reduced by reorienting the barrier and making use of the implicit *hardware guardbands*. The usage of *narrow slits* supports an increased resolution of 50% per eye. Finally, careful selection of *slits* and *duty cycle* allow us to cope with the error introduced by the eye tracking while maximizing the brightness. Portallax also supports a wider working volume, when compared to existing commercial devices. Finally we tested the device for its performance and are able to see that it meets the high requirements we set for retrofitting a handheld device.

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