A Prototype 3D Mobile Phone Equipped with a Next Generation Autostereoscopic Display

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ABSTRACT

The mobile phone is quickly evolving from a communications device to a multimedia platform and in the process has become the focus for the development of new technologies. There is significant interest from mobile handset manufacturers as well as major telecommunications network operators in the development of a stereoscopic 3D mobile phone. The most challenging technical issues for commercializing a 3D phone are a stereoscopic display technology which is suitable for mobile applications as well as a means for driving the display using the limited capabilities of a mobile handset.

In this paper we describe a prototype 3D mobile phone which was developed on a commercially available mobile hardware platform. The demonstration handset was retrofitted with a Polarization Activated Microlens™ array that is 2D/3D switchable and provides both class-leading low crosstalk levels, and suitable brightness characteristics and viewing zones for operation without compromising battery running time. This next generation autostereoscopic display technology, which combines the advantages in brightness and image quality of a lenticular 3D display with the 2D/3D switching capability of a liquid crystal parallax barrier, is deployed on a 2.2'' landscape QVGA TFT-LCD base panel.

The stereoscopic content solution is an essential component of a commercially viable 3D handset. We describe how a range of stereoscopic software solutions have been developed on the phone's existing application processor without the need for custom hardware.

Keywords: 3D, autostereoscopic, display, microlens, 2D to 3D conversion, depth map, mobile, cell phone, content

1. INTRODUCTION

Autostereoscopic display technology provides the potential for the more widespread adoption of stereoscopic display technologies by removing a significant barrier to entry for the average consumer: the need for eyewear. Autostereoscopic displays have been used successfully in public space advertising and entertainment applications but on a relatively small scale. Issues such as brightness, restricted viewing zones, high cross-talk and resolution loss continue to limit glasses-free display technologies.

One of the most promising markets for autostereoscopic display technologies is the mobile platform, for the following reasons:

- Consumers frequently update their mobile devices, facilitating the introduction of new technologies
- Viewing zone limitations are not as significant on a handheld device as the observer can easily adjust the device for comfortable viewing
- Display resolution and pixel densities are rapidly increasing in the mobile display market reducing the impact of resolution loss introduced by spatially multiplexed autostereoscopic displays
- It is a large and potentially lucrative market in which manufacturers are increasingly looking for new technologies to provide product differentiation
- There is a sense that the demographics in the mobile market are receptive to innovative stereoscopic display solutions

NTT DoCoMo released two mobile phone models with autostereoscopic displays based on Sharp's latent parallax barrier[1] in to the Japanese market in 2002/2003. With well over 2 million units sold these products mark a significant milestone in the development of autostereoscopic display technologies.

At the higher end of the market, mobile handsets are quickly evolving from communications devices into multimedia devices. Support for high quality video playback, 3D graphics and GPS navigation continue to broaden the possibilities for stereoscopic content on the mobile platform.

The objective in developing a prototype 3D mobile phone was to demonstrate the effectiveness of integrating an advanced autostereoscopic display into a Smartphone supported by a range of 3D content demonstrations in order to stimulate the development of the next generation of stereoscopic 3D mobiles.

2. DEVELOPMENT PLATFORM

To effectively demonstrate that the component technologies required to build a compelling 3D phone were market ready the prototype was developed on the basis of a commercially available mobile platform. A suitable development platform was selected based on the following requirements:

1. Commercially available in January 2006 (when the prototype was developed)
2. Based on a traditional mobile form factor, with a bright, high resolution, colour display in the 2-2.4'' range.
3. Include a general-purpose application processor (~ 200MHz) for performing stereoscopic rendering functions
4. Running a non-proprietary operating system (e.g. Smartphone) to facilitate code integration

The selected device was the HTC Faraday Smartphone. This device uses a 2.22'' QVGA (240x320 pixel resolution) Thin Film Transistor Liquid Crystal Display (TFT-LCD) in a compact "candy bar" form factor and with an embedded Texas Instruments (TI) OMAP 850 application processor running the Windows Mobile Smartphone operating system. The TI OMAP platform is a dual-core microprocessor for multimedia applications combining both DSP functionality as well as a general-purpose ARM926EJ-S processor clocked at 195MHz, which is well suited to video decoding and processing.

3. MOBILE 3D DISPLAY TECHNOLOGY

3.1 Comparison of switchable autostereoscopic optical technologies

The four main categories of optical components for spatially multiplexed autostereoscopic displays can be categorized as shown in Fig.1, comparing 4-view architectures. Barrier technologies include vertical barriers[2], step barriers[3] and light line[4] type displays, and suffer from low brightness in the 3D mode, poor pixel appearance and diffraction effects which limit the quality of viewing windows, and therefore crosstalk performance and 3D viewing comfort that can be obtained in such displays.

Microlens technologies are best suited to meet the demands of mobile display platforms because of their high optical efficiency and superior imaging performance. Microlenses also enable reflective technologies such as transflective LCD to produce high brightness 3D images.

Both types of switchable microlens display use a birefringent microlens formed from a liquid crystal (LC) layer in contact with a surface relief isotropic material. Active lenses[5] rely on switching an electric field across the LC material inside the lens while Polarisation Activated Microlenses™ switch the polarisation state that falls onto a passive (unswitched) birefringent microlens.

As described in more detail elsewhere[6], Polarisation Activated Microlenses are able to demonstrate high contrast and efficiency and have key advantages over Active lenses for mobile platforms including:

- Improved image quality in 2D mode
- High ruggedness
- Not susceptible to surface pressure
- Ability to make using coating process over large area at low cost
- No difficulties with LC cell sealing and handling

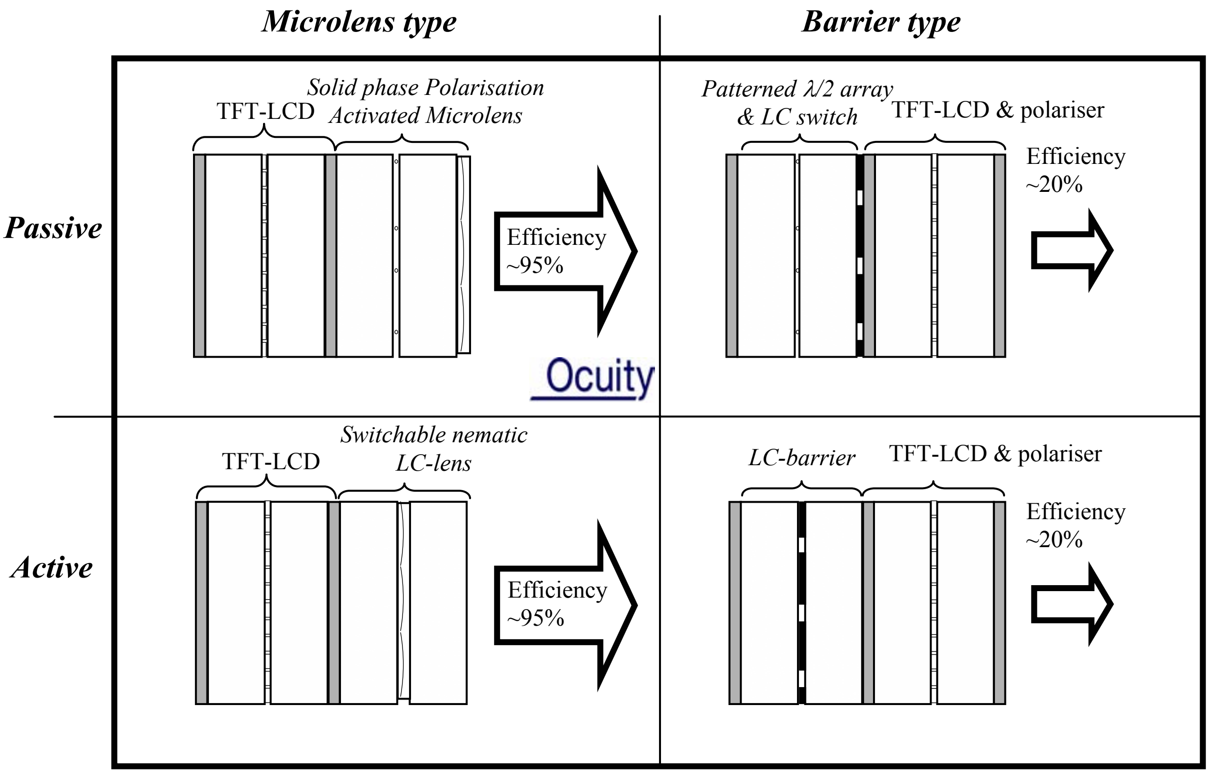


Fig.1 Categories of switchable autostereoscopic display

3.2 Implementation of Polarisation Activated Microlens on Cingular 2125 platform

3.2.1 Panel specification

The display used in the Cingular platform has properties as shown in Table 1. The display in normal mode of operation has a pixel shape and orientation as shown in Fig.2.

Property	Specification
Resolution	(240xRGB)x320, QVGA
Panel diagonal	2.22”
Standard panel orientation	Portrait
Standard pixel orientation	Portrait
Counter substrate glass thickness	0.5mm
Polariser	0.15mm thick, no waveplates
Pixel pitch	0.047x0.141mm
LCD mode	First minimum twisted nematic (TN) TFT-LCD transmissive mode only
Colours	64k (16bit interface)

Table 1 Panel specification for Cingular 2125

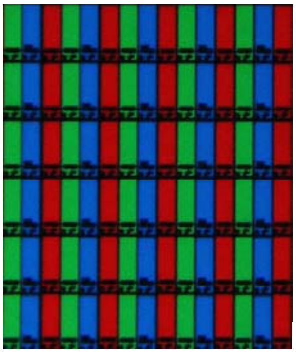


Fig.2 Panel pixel appearance in portrait mode

3.2.2 3D image orientation

Cell phones are usually fitted with portrait displays because of their form factor and for viewing text. However, there are important reasons to use landscape orientation for autostereoscopic 3D implementations:

- The majority of natural images are recorded in landscape (with the obvious exception of portraits) including the key application areas of games, TV and other video content.
- The amount of depth that can be presented on a display is determined by the lateral width of the display that can be used to present disparity information without frame canceling effects – landscape displays can demonstrate more depth.
- Addressing interlaced data onto the rows of a panel is computationally more efficient than onto separate colour pixel columns.
- Landscape mode enables nominal viewing distances of 1/3 of the portrait mode panel with equivalent optical system. Thus a nominal viewing distance (i.e. the distance at which the viewing freedom is a maximum) of 400mm is readily achieved in landscape mode.
- Portrait mode displays can show image stripiness artefacts due to break-up between the separate red, green, and blue channels[7] as shown for example in fig.3. In portrait mode, each colour channel for a pixel comes from a different lens, so that the channels have a wide separation, twice of that in the 2D mode. As each colour has a different luminance function, the human visual system's convolution function results in a resolvable luminance difference, and the image becomes stripy. In landscape mode though, the colour pixel separation is the same as in 2D, and so there is no colour break-up between the separate chromaticity channels.

Consequently, using the Cingular phone in landscape orientation for 3D gives a clear win. In 2D mode, the optic has no optical effect, so the standard portrait mode usage is unaltered.

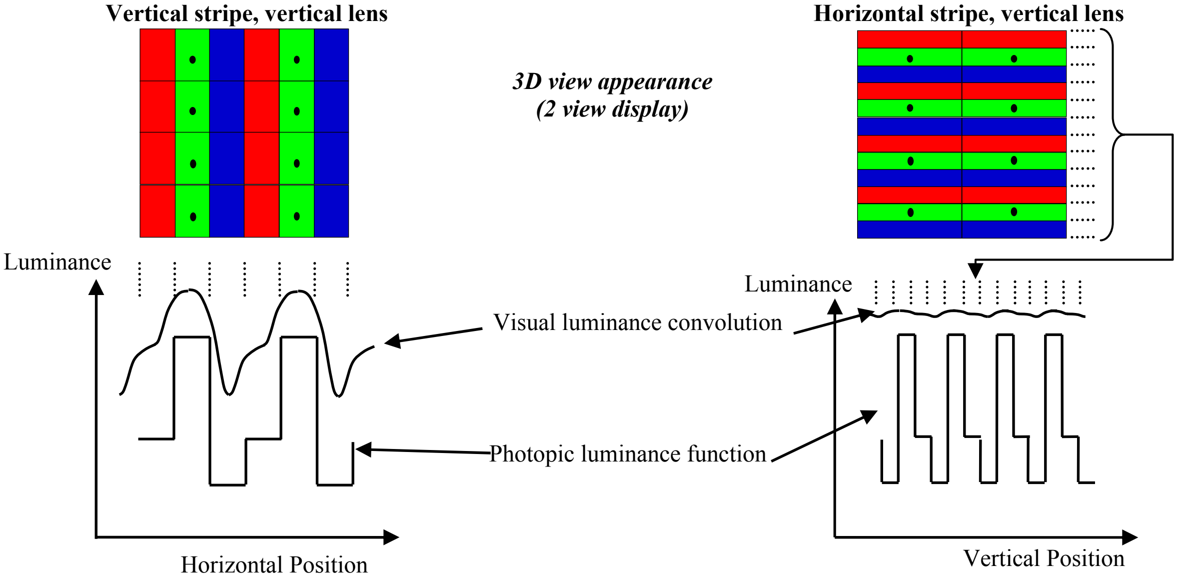


Fig.3 Difference in colour break-up artefact between portrait and landscape 3D orientations for 2-view display

3.2.3 Viewing windows & viewing freedom

Autostereoscopic displays operate by beaming a series of viewing windows towards an observer. The observer sees a single image across the whole of the display with an eye in a viewing window. Each eye sees the light from a different image in separate viewing windows and the brain combines these images to give the appearance of depth.

- Two view displays produce a series of pairs of viewing windows, each with half resolution. Such displays can have cross talk levels of less than 1%, but have limited viewing freedom typically 50mm for well engineered lens display or less for display with poor window quality.

- Multi-view displays present a series of multiple sets of windows, each view with respective lower resolution. Frequency space analysis and optical transparency simulation of resolution trade-offs for multi-view displays are considered elsewhere[7]. This analysis, which was confirmed by practical simulations, concluded that for a 2.22" QVGA panel with stripe colour filters, multiview resolution artefacts are considered clearly visible or very visible.

Optimum image performance for 2.22” QVGA display is thus afforded by a two view landscape display, optimising image cross talk, image blockiness and image stripiness.

3.2.4 Hard spot vs. soft spot

As a two view display is rotated about a vertical axis, the image content switches both in intensity and to a pseudoscopic image[8]. While this is initially unfamiliar, it is the experience of the authors that display users soon get used to this functionality. However, there is a design choice to be made between the nature of the illumination function in the window plane. It is possible to continuously tune the optical design of the lens between an optical power in which the black mask between pixels is sharply imaged (hard spot) and an optical power where it is blurred (soft spot), by modifying the lens radius of curvature and choice of LC and isotropic material refractive indices.

Both types of display have been made and shown to customers with their feedback indicating a preference for hard spot designs; it has been reported that the visibility of the black matrix image between windows helps users more quickly identify the best viewing position. Even inexperienced users seem to do this quite naturally on a cell phone. Furthermore such designs have lower cross talk over a wider range, a key requirement for high viewer comfort.

3.2.5 Optical architecture

In this application, high contrast and power efficiency to maximize battery lifetime are important considerations. Polarisation Activated Microlens architectures demonstrate this performance using the architecture as shown in Fig.4.

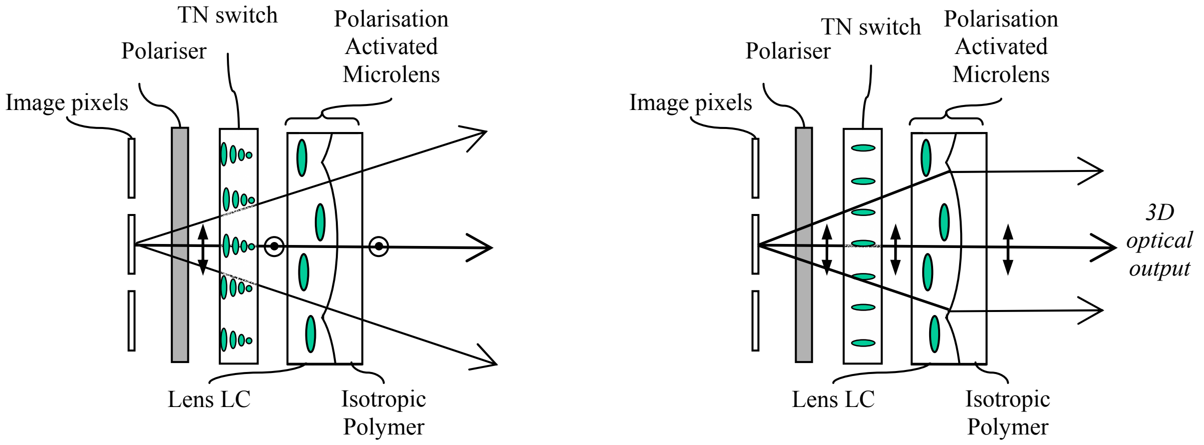


Fig.4 Polarisation Activated Microlens operation

The structure comprises the pixels and output polariser of the base TFT-LCD, a twisted nematic (TN) LC polarisation switch, and a Polarisation Activated Microlens, which has a surface relief structure formed in an isotropic polymer and an adjacent layer of birefringent lens LC. In the 2D mode, the linear polarisation state that leaves the TFT-LCD panel polariser is rotated 90° by the switch LC material and is incident on the normal refractive index of the lens LC material. This has the same refractive index as the isotropic polymer so that there is an index match at the isotropic lens surface, and no optical function is produced by the lens. In the 3D mode, a voltage is applied to the TN switch which reorients the TN switch LC material so that it no longer has a polarisation rotating function. The output polarisation state from the TN switch is incident on the extraordinary refractive index of the lens LC, so that there is an index step at the interface to the isotropic lens, and the lens function is produced.

Losses arise from absorption in the Indium Tin Oxide (ITO) transparent conductors used in the TN switch. High impedance (high transparency) ITO can be used so that these losses can be reduced to a few percent, although standard TN display quality ITO glass was used for the purposes of the prototype.

3.2.6 Device fabrication

In the prototype phone, the switchable 2D/3D element was fabricated as shown in Fig.5 using 3x0.4mm substrate design with an overall thickness of ~1.35mm as shown in Fig.6.

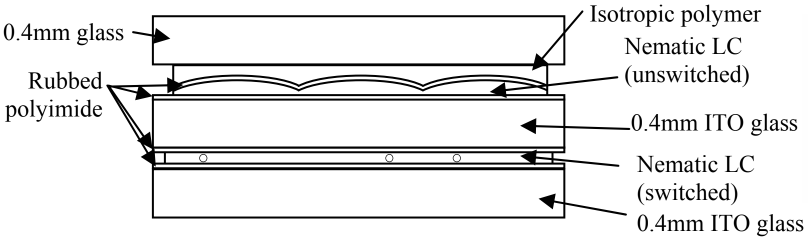


Fig.5 Integrated Polarisation Activated Microlens

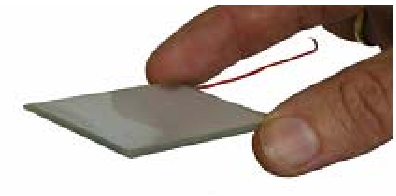


Fig.6 Photo of integrated lens structure

Isotropic lenses were formed by UV casting a commercially available UV curable polymer material onto a glass substrate using a lithographically tooled Nickel shim with radius of curvature design to achieve a hard spot output.

In some devices, segmented electrodes were implemented in the TN switch to allow mixed 2D and 3D output, with similar brightness achieved in both modes.

Typically, the output polarisation state of a transmissive TN display is at 45° to the vertical. By controlling the alignment orientations at the plane surface of the LC lens, the incident polarisation state undergoes a twist in the lens such that the LC can then be aligned parallel to the lens axis at the structured surface[9], optimising alignment performance.

The alignment orientations in the lens can also be used to set the default (power-off) optical output. For ease of demonstration, the device was set to have zero power consumption in 3D mode; however, the alignment orientation at the lens plane surface would typically be set for default 2D mode operation, with a powered 3D mode.

In operation, the LC material in the lens remains homogeneously aligned and so there is not residual unswitched LC material near to the lens cusps in the 2D mode, providing a significant image quality advantage for Polarisation Activated Microlens technologies over Active lens technologies. More details of fabrication methodologies for this component are described elsewhere[6].

In the prototype, the TN switch LCD is controlled from an external digital oscillator circuit which provides a low voltage, low frequency signal to drive the switch cell. The switch cell (power-on) consumption is below 1mW. In production devices, this circuit function is easily integrated along with an input signal to control operation in 2D or 3D from software.

3.2.7 Subsequent processing developments

Substantial advances in the manufacturing route for this technology are reported elsewhere in which the unswitched nematic LC is replaced with cured polymer LC[6]. This enables:

- Low cost over large areas using a new coating technology, enabling motherglass processing
- Substantial reductions in device thickness
- Increased ruggedness

Such elements can be combined with commodity TN switches, substantially simplifying device complexity and reducing cost in a manufactured product.

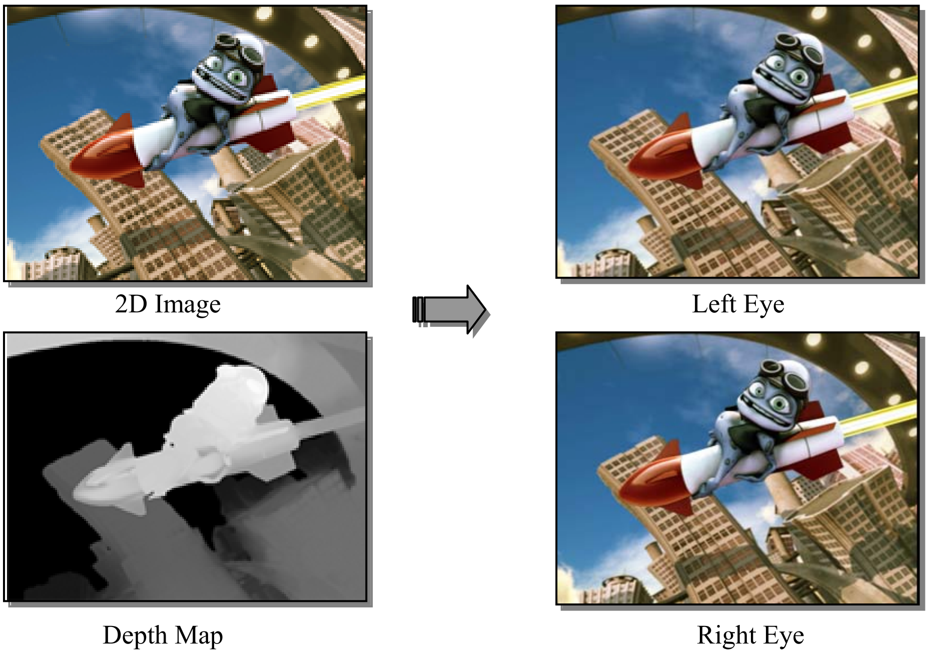
4. MOBILE 3D CONTENT

The applications of stereoscopic 3D on mobile phones are primarily directed at entertainment applications including 3D images or wallpapers, MMS, videos and gaming. The main development focus for the prototype 3D handset was to enable support for high quality stereoscopic video. Mobile devices now routinely support video playback. Developments in mobile TV based on broadcast standards such as Digital Media Broadcast (DMB) as well as the advances in 3G/3.5G networks have encouraged the more widespread adoption of video capable handsets. These developments provided the necessary framework for the development of a 3D video capability.

4.1 2D to 3D conversion

It is widely acknowledged that a 3D mobile phone must be supported by a range of current and compelling 3D content in order to be commercially successful. DDD has previously published details of its off-line 2D to 3D conversion technologies in this forum[10]. These tools are primarily designed to assist in the identification and tracking of objects in a motion sequence through which a depth map is associated with each image frame.

Using depth maps to render virtual stereoscopic images has been described by Harman[11] within the context of home based 3D entertainment. Fehn[12] also proposed Depth-Image-Based-Rendering (DIBR) as the foundation of an advanced 3D TV system. This basic process of rendering stereoscopic images using a depth map is illustrated in Fig.7. The image in the top left hand of Fig.7 shows the original 2D image. The depth map was created using DDD's 2D to 3D conversion technologies[10]. The virtual stereo pair on the right hand side of Fig.7 were synthesized from the original 2D image using a depth based render.


2D Image

Left Eye

Depth Map

Right Eye

Fig.7 Overview of depth based rendering: virtual left and right eye images are rendered from a depth map and the original 2D image at QVGA resolution

In order to provide relevant content to support a 3D mobile market DDD has partnered with leading 2D mobile content publishers and aggregators like Jamster!. High quality 2D to 3D conversion tools were used to create an extensive stereoscopic content library of over 200 3D content pieces encompassing video, MMS and wallpapers, which can be used to support the demand for 3D mobile content.

4.1.1 Real-time conversion

There has been significant interest in the ability to convert 2D content to stereoscopic 3D in real-time (i.e. at video rates). There are a number of reasons why this approach is so attractive:

- It opens up a much broader range of stereoscopic content
- There is no cost or time delay involved in conversion
- Content can be encoded and transmitted using existing 2D video formats

Recovering 3D information from a sequence of 2D images is complex, unreliable and error-prone. The quality of stereoscopic content produced using real-time conversion is therefore generally lower than content converted using off-line (human assisted) conversion. Despite this limitation real-time conversion continues to play a significant part in meeting the demand for stereoscopic 3D content. DDD developed a real-time conversion process as part of the software bundle for Sharp's AL3D autostereoscopic notebook[13], providing the means for automatically converting standard DVDs from 2D to 3D. The process was based on the automatic recovery of depth information from an image sequence by analyzing the color and motion characteristics of identified objects. A limited implementation of the same algorithm was developed to support the real-time conversion of 2D video content within the prototype 3D handsets application processor.

4.2 Stereoscopic encoding formats

A stereoscopic conversion and rendering library was developed to support three basic encoded media formats:

- Tiled pre-rendered stereo image pairs
- Asymmetric tiled 2D video and depth data
- 2D video converted to 3D using real-time conversion

4.2.1 Pre-rendered stereo

For the Polarisation Activated Microlens display stereo images are rendered into the display buffer in a vertically interlaced format with each alternate column representing data from the left and right eye. Standard (lossy) compression techniques, based on quantizing DCT coefficients, are not effective at directly encoding such interlaced formats. Pre-rendered stereo pairs are therefore encoded using a spatial tile in which the left and right eye images are encoded side-by-side in a 320x240 (landscape QVGA) image frame by horizontal rescaling.

After decoding the image frame the stereo pairs are vertically interlaced on the handset at video rates. The loss of resolution due to spatially tiling the stereo pair into a single image frame is minimal as the image is re-sampled in the same direction as vertical interlace in the frame buffer.

4.2.2 Depth encoding

There are a number of advantages in supporting depth-encoded media within the context of mobile 3D:

- Depth maps can be effectively compressed to provide a bandwidth efficient stereoscopic transmission mechanism[14,15]
- As the original 2D video is transmitted unaltered the encoding format is inherently backward compatible with 2D display devices
- The depth effect can be adjusted to suit individual preferences as virtual stereoscopic views are rendered in real-time during video playback

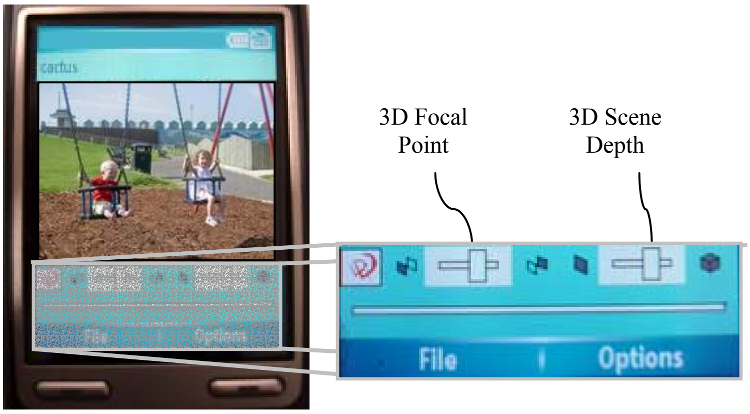


Fig.8 Illustrating the Media Player application running on the 3D handset with a close up of the user controls.

Fig. 8 shows a Media Player running on the 3D handset. The close-up of the interface on the right hand side shows the controls for modifying the zero parallax position (3D Focal Point) as well as the overall disparity (3D Scene Depth) when rendering from depth based representation. These controls enable the user to interactively configure the render to ensure a comfortable 3D viewing experience.

To fully realize the bandwidth efficiency of a depth based encoding scheme it is necessary to encode depth data in a separate video stream. However, for the sake of simplicity, depth data is encoded in an asymmetric side-by-side format alongside the 2D video signal. This encoding format provides the best compromise between data fidelity and decoding/rendering overhead for depth encoded content.

4.2.3 Content applications

These three encoding formats provide a broad range of options for stereoscopic video on the handset:

1. Original stereo content can be encoded as side-by-side pre-rendered stereo, as described above. This content may have been originated using stereo cameras (either physical or virtual) or by some other 2D to 3D conversion process
2. Depth encoded content can be efficiently transmitted across bandwidth limited networks (such as DMB/DVB-H networks). The depth data may have been created using an offline conversion process or using a depth map camera[16]
3. Real-time conversion can be used to convert any existing 2D content to 3D on the handset

It should also be noted that the stereoscopic encoding formats supported on the 3D handset are designed to be open, not proprietary, with the aim of encouraging growth and diversity in the stereoscopic mobile content marketplace.

4.3 Software Integration

The stereoscopic conversion and rendering library is referred to as TriDef™ Frame Renderer SDK and is a software component that is integrated into the 2D video processing pipeline on the 3D handset. Fig.8 illustrates how the TriDef Frame Renderer SDK is integrated into a media player application. The library receives uncompressed image frames from the decoder and renders 3D interlaced images directly into the frame buffer, based on the stereoscopic encoding format.

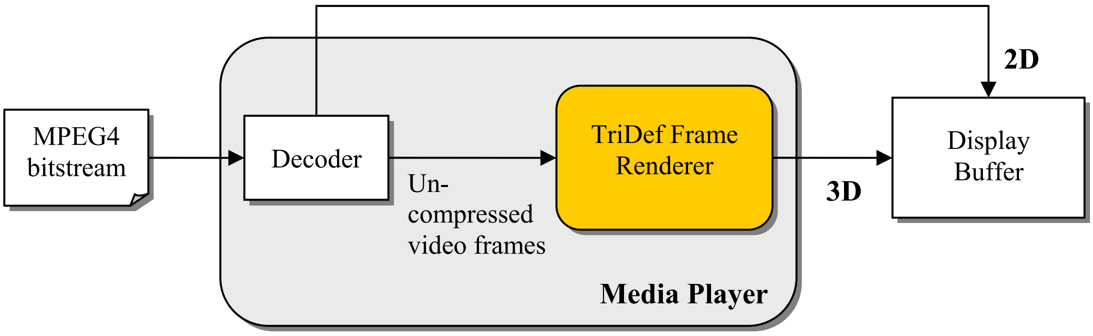


Fig.8 2D and 3D processing pipeline showing integration of TriDef Frame Renderer SDK with media player application

It should be noted that this framework supports a number of different 2D image and video codecs. The TriDef Frame Renderer SDK can also be integrated with any other application on the handset that processes image or video data including camera interfaces, mobile TV applications and web browsers.

5. PERFORMANCE ASSESSMENT

The performance characteristics of a number of codecs were evaluated both in terms of processor load and image quality on QVGA content. An MPEG-4 (simple profile) codec was selected as it provided good image quality without significant blocking artifacts while keeping the load on the main application processor within manageable limits. A variable bit rate of approximately 500Kbps was used to encode both 2D video content as well as stereoscopic video content.

Experiments conducted by Fehn[15] show that encoding depth maps using MPEG-4 does not lead to significant stereoscopic rendering artifacts, unless the bit rate is very low. As the depth maps are encoding within the RGB image frame the bit rate was more than adequate to ensure the virtual stereoscopic views were free from blocking artifacts.

The graphs in Fig.9 illustrate the utilization of the ARM926EJ-S application processor for a number of stereoscopic rendering and 2D to 3D conversion tasks. The least intensive task is rendering left/right stereo encoded image pairs as this only requires a simple remapping of pixels from the input image into the spatially multiplexed mask image. The process represents an additional overhead of around 25% over and above MPEG-4 video decoding.

The depth based render requires more computation as the process involves selective pixel remapping based on an interpolated depth value. Despite substantial optimization the process represents an overhead of approximately 30% over video decoding. Real-time conversion estimates a depth map as described above and uses the depth based render module to produce a stereoscopic image.

Both the source and depth render engine and the real-time conversion module can be configured by a quality parameter to trade-off execution speed for render quality. Figure 10 shows timings for the combined real-time conversion and depth render engine. The graph shows that a broad range of performance can be achieved, which is useful for maximizing image quality when porting the process to other mobile devices with more or less performance as well as fine-tuning depending on content.

The results indicate that the 195MHz ARM926EJ-S core provides adequate performance for rendering QVGA content:

- 24 frames/sec for stereo encoded content
- 24 frames/sec for source and depth encoded content
- 15 frames/sec for real-time 2D to 3D conversion and rendering

It should be noted that many of the commercial mobile TV deployments involving both DMB and DVB-H were based on 15 frames/sec video so the reduced frame rate for real-time conversion on the handset is not a significant limitation[17].

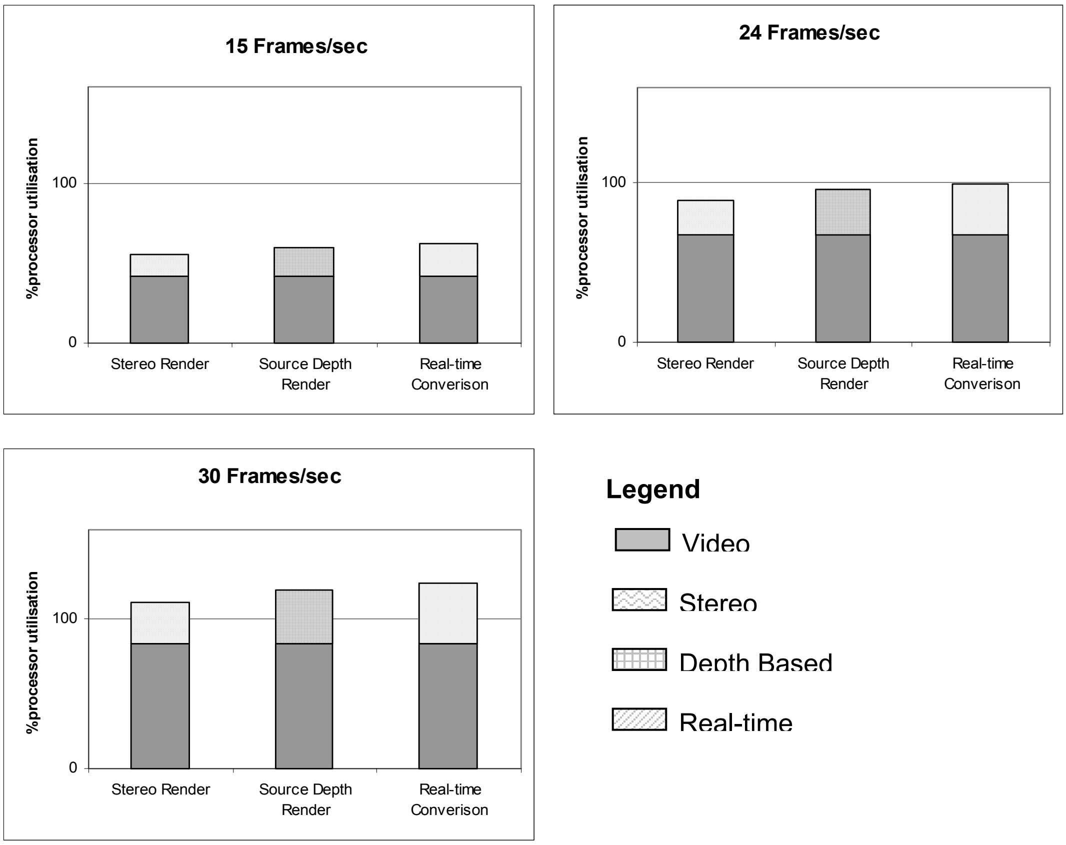


Fig. 9 Performance analysis for 3D video decoding and rendering on the ARM926EJ-S 195MHz processor: a) 15 frames/sec, b) 24 frames/sec and c) 30 frames/sec

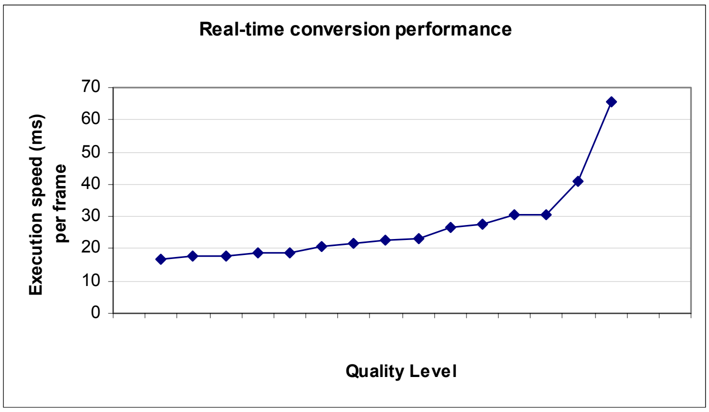


Fig.10 Scalable Real-time conversion/render performance on ARM926EJ-S 195MHz core

A primary design decision for the future development of mobile 3D devices relates to the use of custom hardware for stereoscopic conversion and rendering. Although custom hardware has the advantage of implementing specific tasks much more efficiently than software running on a general purpose processor this has to be balanced with a number of other considerations:

- Increase in system design complexity caused by the introduction of an additional custom chip. Existing handset designs must be modified to accommodate the additional chip area
- Gains in efficiency are offset to some extent by the requirement for data transfer between the video decoding system (generally running on the application processor) and the stereoscopic rendering system
- Increased complexity for software development to coordinate scheduling of tasks across multiple processors

It is becoming increasingly common to integrate graphics processors (GPU) on high-end multimedia handsets. Stereoscopic rendering tasks such as the source and depth DIBR render have been implemented using mobile graphics cores supporting OpenGL ES and can be used to reduce the load on the application processor. However, on mobile platforms the inter-connect between the application processor and the GPU is often unable to transfer full QVGA video textures at 30 frames/sec, making such hybrid rendering system infeasible.

The ARM926EJ-S application processor includes a set of DSP enhanced extensions. These extensions are targeted to improve the efficiency of digital signal processing techniques without requiring a separate (off-chip) DSP and effectively lie somewhere between software and custom hardware. The extensions have been shown to provide a substantial performance improvement for common audio and video decoding tasks[18]. The MPEG-4 decoder used in this prototype did not take advantage of these extensions: an optimised decoder would free up additional cycles for stereoscopic conversion and rendering tasks.

Implementing stereoscopic conversion and rendering on the application processor provides a tight integration between the video decoding stage and has significant benefits in reduced system complexity that translates to faster time-to-market for handset manufacturers.

6. CONCLUSION

DDD and Ocuity collaborated to produce a prototype 3D mobile Smartphone. The 3D phone featured a 2D/3D switchable display which is full brightness in 2D and 3D and has cross-talk of order 1% in 3D mode. This low cross is key to the superior visual performance of the phone, and it means that an excellent amount of depth to be shown for a wide range of content images without noticeable ghosting. Through the integration of efficient conversion and rendering software with the handset's main application processor it was possible to playback 24 frames/sec QVGA video content rendered in real-time using optimized depth based rendering techniques. This means that provision of content is no longer an issue for 3D handsets. The phone's primary purpose was to provide a benchmark for handset manufacturers and telecoms carriers to assess the commercial viability of a stereoscopic 3D phone using technologies that are available and ready for mass production as of 2006.

Due to the rapid evolution of mobile technologies the optimal platform is evolving. In particular, the emergence of graphics cores and other multimedia hardware acceleration will expand the range of possibilities including 3D gaming and navigation applications for stereoscopic 3D mobile.

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