Super multi-view augmented reality glasses

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ABSTRACT

Nowadays, the main directions of augmented reality (AR) glasses development are: increasing of field of view (FoV) and eye-motion box; reducing weight of AR glasses; solving vergence-accomodation conflict. All these requirements should be obtained and combined with high image quality and decreasing dimensions of AR Glasses. We propose the optical system of AR glasses based on Schmidt Camera scheme for achievement of wide FoV and eye-motion box, and with using of Super Multi-View (SMV) technique for providing multifocal system. Provided optical design has huge benefits: eye motion box about 10 mm and field of view 60° and represents lightweight, eye fatigue free solution with low aberrations. Finally, our system has high opportunities for further modifications and improvements by using different image sources and projection system.

Keywords: augmented reality, head-mounted display, near to eye display, super multi-view, multi-focus, optical design

1. INTRODUCTION

Augmented Reality (AR) is technology of overlaying computer generated information on the real environment in the real time [1, 2, 3]. The virtual reality, represented by optical AR devices may contain text information, graphic image, information about real objects observed within field of view of a device. The first augmented reality system using optical see-through head-mounted display (HMD) was invented by Ivan Sutherland in 1968 [4]. For constructing AR HMD with natural perception of 3D images it is necessary to consider the features of human visual system. It is known, that pupil size changes from 2 to 8 mm in diameter depending of environment illumination [5]. Angular resolution of the eye is 1 arcmin, field of view for one eye is 60° nasally and 100° temporally, binocular field of view is 120° [6], near accommodation point of the typical eye is placed on distance 254 mm [7], center of eye rotation is 13-15 mm behind cornea [5, 6], optimal required eye rotation for devices is ±15°. Design of AR HMD considering all human visual system factors will help to build comfort viewing and full immersive system.

Human perception of the depth relies on four factors, which can be split in two categories: optical depth perception by eye and brain image processing [8]. Optical depth perception include vergence, binocular disparity and monocular accommodation mechanisms. Brain image processing include complicated transformation of motion parallax, which is due to observer position, object texture, illumination, and perspective of space. Therefore, vergence, binocular disparity and monocular accommodation are optical factors which provide perception of natural 3D images, and motion parallax is important for viewer freedom of eye movements. Mechanism of binocular disparity is uses in every AR HMD – for right and left eye different images are projected. Difference in images depends from object distance from viewer. When viewing object on some distance, the axis of eyes converges so that object is imaged on fovea of both eyes [7]. This mechanism is one of major factors for human depth perception. Monocular accommodation is mechanism of changing focus of the eye for objects placed in different depths, this mechanism can be perfectly done by holographic 3D displays. One of the problem of AR HMD is vergence-accommodation conflict (VAC), which provide eye fatigue during prolong use [9]. VAC appears when axes of eyes converges on virtual image plane and accommodate on the display plane, and these planes don’t match. For solving this problem different techniques are applied [9].

Important issue in development of AR HMD is providing multifocal system. In the beginning of 20th century Lipmann [10] proposed method of integral imaging, which operates with reproduction of light fields providing correct depth cue for viewer. This method was applied for constructing optical see-through head-mounted display with using of free-form optics.

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[11] with image depth range over 4 meters. Liu at al. [12] demonstrated HMD with addressable focal planes using active optical element – liquid lens in combination with spherical mirror. Focal plane range in this system is 16 to 100 cm. R.Konrad et al. also demonstrated system with tunable lenses with opportunity to accommodate on the distances from 10.5 cm to infinity [13]. Deformable membrane mirrors provide varifocal focus mechanism and accommodation depth range can achieve from 0.25 to 5 meters [14]. Holographic optical element (HOE) in combination with movable spherical mirror can provide compact varifocal system [15].

Y.Takaki et al. presented multifocal system using super multi-view technique with accommodation distance range from 0.3 to 5.0 m, 0.3 – 0.6 m and 1.0 – 12.7 m in different configurations [16]. An SMV display generates dense viewing zones with pitch smaller than eye pupil diameter [17]. Each zone corresponds to its view. Because the viewing zones are smaller than eye pupil, when eye moves from one point to another the retinal image changes smoothly, that provide discount of motion parallax. High-density directional display (HDD) with generation viewing zones at the infinity were proposed [18-20]. Head-mounted type SMV display was proposed [21]. SMV technique was applied to construct the windshield display with 36 viewing zones [22].

In this report we present concept design of AR glasses with using of SMV technique for providing absence of VAC and large accommodation depth range.

2. CONCEPT AND DESIGN

There are two basic approaches to design optical system of AR glasses: simple magnifier and compound microscope, our scheme is based on first one. Basically, simple magnifier represent positive lens, in our case we use concave spherical mirror. If display is placed in the focal plane of the mirror, virtual image appears in the infinity. Simple magnifier has some advantages: low weight and low cost. Concave mirror used as simple magnifier allow to decrease distortions.

The key idea is to use concave spherical mirror to project display image to the eye (fig.1, a). Display places in the focal plane of the concave spherical mirror directly in front of viewer’s eye. If the exit pupil of the system is small enough relatively to diameter of the concave mirror, then aberrations in the system are insignificant. This system also called Schmidt Camera system [23]. The display in this system represent transparent screen - we propose to use holographic optical element (HOE) in combination with optical projection system.

![Fig.1 Optical layout](image)

Fig.1 Optical layout a) conceptual layout of AR glasses based on Schmidt camera telescopic system. System has wide FoV, large eye-motion box; b) Schmidt camera telescopic reflector system, aperture diaphragm MN is placed in the plane of center of curvature O of spherical mirror B. Axis’ s of beams passed through the diaphragm are matched with the curvature radius of mirror B, focal points of these beams forms geometrical locus of points FF'. This system is free from coma and astigmatism distortions.

Schmidt camera system is telescopic reflector system, where aperture diaphragm MN is placed in the plane of center of curvature O of spherical mirror B (fig.1, b). Axis’ s of beams passed through the diaphragm are matched with the curvature radius of mirror B, focal points of these beams forms geometrical locus of points FF’ with curvature radius half as spherical mirror B. This system is absolutely free from coma and astigmatism, has wide field of view and provide large eye-motion box [23]. Using of such scheme in AR HMD can provide opportunity for constructing small projection system. Field curvature can be compensated either by programming method or by using of curved HOE, with curvature radius twice less than curvature of spherical mirror.
Holography is the most suitable technology for AR see-through applications. HOE has high transmittance, high angle and wavelength selectivity, high diffraction efficiency. The function of conventional optical elements can be recorded on the holographic material by interference between signal and referent waves [24]. Signal wave is then reconstructed by illumination of HOE by wave with the same angle and wavelength as reference wave. Optical element can represent lens or lens array, image formation of such scheme present on the fig.2 (a). Based on holography capabilities, HOE diffuser is proposed to be used as a display (fig.2, b).

Optical system of static concave mirror and HOE diffuser form image either on the finite distance or in the infinity. Some methods can improve this system and make it multifocal. Movable mirror [15], using of deformable mirror [14] provide variable focal length. However, these techniques require additional mechanism for mirror movement, which can be bulky, noisy and energy consuming. For avoiding these problems, we propose to use another technique for making system multifocal. Instead of standard HOE diffuser, we propose to use directional HOE (DHOE) diffuser, which operates as multi-view display [16, 22, 25-26].

Integral imaging is one of the promising technique, reproducing light fields by using lens-array, which convert the spatial information into angular [27] (fig.3). This principle can provide correct depth perception of 3D images for human visual system. Lippmann presented optical system based on such technique in the beginning of 20th century [10]. Lenticular lens in combination with conventional display is used in AR applications to obtain full parallax images. Lenticular lens allow to construct the super multi-view (SMV) display, which project numerous parallax images with rays converging with nearly parallel beam to viewing zones [25].

SMV technique was developed to construct a natural 3D display with absence of accommodation-vergence conflict (VAC) [22]. Multi-view display generates multiple viewing zones where corresponding parallax images are viewed. Viewing zones are discrete, parallax image changes when eye moves along the viewing zones. Discontinuity of motion parallax is represented by viewing angle Δφ. Pitch of viewing zones d is equivalent to width of each viewing zone and...
should be smaller than eye pupil. Thereby, if at least two viewing zones provide passing rays through one point of 3D image and enter the pupil simultaneously, than eye can focus on that point according to vergence distance of 3D image.

Fig. 4 Discount of motion parallax provided by SMV technique. The distance between observer (viewing zones) and display plane represented by l, the distance between observer and 3D image plane is represented by z. Period of the viewing zones is the same as width of the viewing zones and denoted by d. Parallax images for every viewing zone are displayed on the display plane. When eye position changes from point A to point B, 3D images changes according to motion parallax providing depth perception.

SMV technique implies using of lenticular lens, however its using in see-through AR glasses is limited, because in case of AR glasses lenticular lens refracts not only required image light field from display, but also light from environment. For solving this dilemma, the HOE is proposed to use instead of conventional display with lenticular lens. HOE represent hologram which operates as conventional optical element in Bragg’s match condition [24]. HOE has high transparency and high angle and wavelength selectivity that provide viewing of both virtual and real images without aberrations. According to Kogelnik coupled wave theory [24] diffraction in thick hologram is carried out when Bragg-condition is satisfied. In this case maximum diffraction efficiency can be achieved. There are two types of HOE: transmission and reflection (fig. 5). In our case transmission type HOE is more suitable in cause of narrow working boundaries of Bragg’s condition in comparing with reflection HOE (fig. 5), that provide less diffraction of environment light field. Also transmission type HOE would be more compact in optical scheme of AR glasses, if projector will be placed in the glasses temples.

Fig. 5 The angular and wavelength selectivity of lossless dielectric grating normalizes Off-Bragg parameter, as function of $\xi$ (parameter of wavelength and incidence angle) for different values $\nu$ (parameter of oblique factors of hologram illumination) a) for transmission grating; b) corresponding graph for reflection grating

Function of lens-array can be recorded using coherence light source [24, 27]. Plane signal wave passes through lens-array and converges light as shown on fig. 6 (a). Signal and reference waves incident at the photopolymer attached at glass substrate at the same time and form interference pattern. Reconstruction of the signal wave occurs by plane wave, which has the same wavelength and angle of incident as reference wave – satisfies to Bragg’s conditions (fig. 6, b). Therefore reflection type HOE regenerates wave front of lens-array. The diffraction efficiency of the HOE can achieve above the 90%. The value of diffraction efficiency depend of recording conditions. Transparency of HOE for Bragg-mismatched light is near 90%. Recording of proposed transmittance HOE by analogue method has some issues: manufacturing of lens array with lens small pitch is complicated and expensive, recording setup is complicated. Using of holographic printer scheme could be solution (fig. 6, c) [28]. The signal wave from the SLM and lenses is recorded as lenslet of lens array. After recording of elemental volume hologram HOE shifts on the printing pitch with motorized two-axis linear stage. Recording properties can be adopted to customize specifications.
3. SIMULATION AND RESULTS

In this section, calculations of parameters of super multi-view AR glasses and simulations are reported. At first, we should calculate parameters of optical system satisfied the condition of SMV display. Y. Takaki described in details method of calculation characteristics of multi-view display [16, 22]. We assume that nearest depth for perceiving 3D image \( z_n = 300 \) mm, and furthest depth \( z_f = 6000 \) mm, then we can calculate the distance from viewing zones to display plane [3]:

\[
\frac{1}{l} = \frac{1}{z_n} + \frac{1}{z_f}.
\]

In our case \( l = 571.43 \) mm.

Scheme of the imaging system is explained on the fig. 7. Projection mirror forms two images: virtual image of the display and virtual image of the viewing zones. The width of multi-view display is denoted by \( D_0 \). Distance between display and viewing zones is denoted by \( l_0 \), total width of the viewing zones is \( W_0 \). Distance between viewing zones of the observer and virtual image is denoted by \( l \), distance between viewing zones and projection mirror is denoted by \( h \) and distance between multi-view display and projection mirror is denoted by \( s \). Total width of the virtual image plane is denoted by \( D \). Focal length of the mirror is denoted by \( F \).

Display size and position as well as size and position of virtual image can be calculated from:

\[
\frac{1}{s} + \frac{1}{l-h} = \frac{1}{F},
\]

\[
\frac{1-h}{s} = \frac{D}{D_0}.
\]

Then, to calculate viewing zones, we employ more equations:

\[
\frac{1}{h} + \frac{1}{l_0+s} = \frac{1}{F},
\]

\[
\frac{l_0+s}{h} = \frac{W_0}{W}.
\]

Number of viewing zones is denoted by \( N \), pitch of the viewing zones for observer is denoted by \( d = W/N \). Total number of pixels is denoted by \( X \times Y \), pixel pitch of the virtual image is denoted by \( p = D/X \).
Virtual image plane

D

Projection mirror

Multi-view display

Viewing zones

Viewing zones of multi-view display

Fig. 7 Imaging system of super multi-view AR HMD: concave spherical mirror is used as projection lens, multi-view display represents DHOE.

We determine that total width of the viewing zones of observer is the same as eye-motion box of the system – 10 mm. We suppose that standard eye pupil has diameter 2 mm. SVM technique implies rays of at least two viewing zones pass through the eye pupil. That means, that width of one viewing zone is 1 mm and total number of viewing zones is $N = 10$ (fig. 8).

Fig. 8 Distribution of viewing zones regarding the eye

Spatial light modulator (SLM) with resolution 2056x1088 can be used in this system as a source of the projection block. Size of the $D_0$ is calculated based on target FOV of the system (60°) and the distance $h$ (fig. 7). We assume that $h = 50$ mm and $s = 25$ mm. Then $D_0 = 29 \times 18$ mm. Pixel pitch of the display $p_{D0} = D_0/2056 = 29/2056 = 0.014$ mm. If SLM pixel pitch is 0.0063 mm, then magnification of projection system should be 2.22x.

Equation 2 allow to calculate focal length of the spherical mirror, and it is 23.86 mm, therefore curvature radius is 47.7 mm. From equation 3 we determine size of the virtual image, and it is 605 mm. Equation 4 allow to determine $b_0 = 1012$ mm and from equation 5 total width of viewing zones of multi-view display is $W_0 = 602$ mm, period of the viewing zones is $d_0 = W_0/N = 60$ mm.

Amount of viewing zones $n$ corresponds to amount of viewing zones in pixel group. That means, that resolution of 3D image will be decreased in $n$ times. If splitting of the display pixels is performed in one dimension (for example horizontally) than 3D image resolution will be decreased in $n$ times in one dimension. We suppose to split pixels in two dimensions, forming pixels group 2 x 5 pixels (fig. 9, a), then horizon resolution of 3D image will be decreased in 2 times and vertical in 5 times, the number of pixels of 3D image for every viewing zone is 1032x217. For each zone $z_i$ only one vector containing $k$ number of angles ($k$ - horizontal resolution of single view image) should be calculated $[\phi_{1z_i}, \phi_{2z_i}, \ldots, \phi_{kz_i}]$ (fig. 9, b).
Fig. 9 Viewing zone formation a) display pixels groups 2x5 pixels form 10 viewing zones; b) each zone has only one vector containing k number of angles \( \varphi' \).

Direction diffuser light angular distribution in vertical direction is assumed to fill 1mm eye box – corresponding to one viewing zone, and doesn’t need to be calculated. Therefore, multi-view zones are formed by selective angular distribution in horizontal direction. Thus, directions for each pixel can be calculated, for instance, in CODE V software based on real raytrace with \( \text{rayrsi}(\text{zoom_pos}, \text{wave_num}, \text{field_num}, \text{ref_surf}, \text{input_array}) \) function through for-loop iteration, where: \( \text{field_num} \) is pixel position from \( n \times m \) matrix containing position of each pixel; \( \text{ref_surf} \) is plane of eye-box; and \( \text{input_data}(1) \) is position of each viewing zone (relative pupil x coordinate).

Macros for calculation of slanted angle \( \varphi \) looks like this:

```plaintext
for \( i = 1 \) to 10 // iteration from number of viewing zones
   for \( j = 1 \) to \( n \) // iteration through pixel
      \( \text{ref_data}(1) == \text{zone_pos}(i) \)
      \( \text{ok} == \text{rayrsi}(1,1,\text{pixel}(i,j),\text{eyebox_plane},\text{input_data}) \)
      \( x_s2 == (x s2) \) // X coord of intersection with mirror
      \( z_s2 == (z s2) \) // Z coord of intersection with mirror
```

Then \( \varphi'_{zi} \) – slanted angle of DHOE, can be calculated from intersection point \( x_s2, z_s2, \text{pixel}(i,j) \) and \( s = 25\text{mm} \) (distance from DHOE to concave spherical mirror) (fig. 10):

\[
\varphi(i,j) = \frac{180}{\pi} \cdot \arctan \left( \frac{x_s2 - \text{pixel}(i,j)}{25 - z_s2} \right).
\]  

Fig. 10 Configuration of the super multi-view AR glasses. Projector transfer image form SLM at the plane of multi-view display, which represent directional holographic optical element (DHOE). DHOE redirect beam of every pixel on the concave spherical mirror with angle \( \varphi \). Angle \( \varphi \) determines viewing zones position and can be calculated using coordinates of virtual image pixel and point of intersection the concave spherical mirror \( x_s2, z_s2 \). Total width of viewing zones correspond to eye-motion box of the system. Virtual image of the display forms on the fix distance \( l \). Image presentation on the different depth occurs by displaying specific images on the SLM.
Optical system modeling was done using CODE V software (fig. 11). Design of optical system was done in backward mode, when virtual image represent “object”, and DHOE represents “image”. Calculated parameters of concave spherical mirror provided high MTF at the DHOE plane in central zone, but MTF significantly dropped to the edges of the DHOE. Optimization of mirror shape to aspherical type allows to achieve higher MTF at the full DHOE plane.

Fig. 11 AR glasses system modeling overview: a) beam path in the optical system of AR glasses, every color corresponds to specific viewing zone; b) MTF graphic at the plane of DHOE for different field points, the minimum value is 17.3 cycles/mm correspond to the edges fields of virtual image, the average value for MTF is 50 cycles/mm.

4. CONCLUSION

In the course of implementation, design of AR glasses was proposed. Using of concave aspherical mirror provides wide horizontal FoV – 60° and large eye-motion box – 10 mm. Super multi-view technology provides multifocal system with depth range from 30 cm to 6 m. HOE display provide high transparency and high efficiency system. Proposed system is free from VAC and coma and astigmatism aberrations. Current scheme can be improved by using of higher resolution display for achievement higher resolution 3D images and using of computer generated hologram (CGH) method for providing natural high-density data 3D images.

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