Eyeglass display design based on freeform optical surface

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1. Marketing Requirement:

There are a lot of research groups and companies all over the world devoted their effects into the area of head mount see through devices, and all kinds of different designs from curved mirror to polarized waveguide come out in the past years. According to the Transparency Market Research by Albany NY, "Head Mounted Display Market -Global Industry Analysis, Size, Share, Growth, Trends and Forecast, 2013- 2019" the market was valued at USD 342.7 million in 2011, and is expected to reach USD 9,275.4 million by 2019, growing at a CAGR of 55.3% from 2013 to 2019.[1] Notable methods and products will be listed as following which based on different waveguide, curved mirror and projection approach.

1) Reflective Waveguide (use TIR through the waveguide and semi reflective mirror to couple into eye)[2]
   a. Google Glass(MyOptical/MyVu)
   b. Epson Moverio (meta)
   c. Optinvent Clear-Vu

   Advantage: Good image uniformity; less light loss;
   Disadvantage: thick light guide.
2) Polarized Waveguide(use multilayer coatings and embedded polarized reflectors in order to extract light toward pupil)
   a. Lumus

   Advantage:Large FOV as well as eye motion box;
   Disadvantage: Expensive; Color non uniformity;
3) Diffraction and holographic waveguide
   a. Nokia Vuzix/Mirage Innovation (slant grating to couple the light in and out)
   b. Sony(sandwiched holograms)
   c. Konica Minolta
   d. SGB Labs Digilens DL40(Switchable Bragg Grating nanocomposite materials)
   e. The Technology Partnership(projection into lens that contains an embedded grating structure)

   Advantage: works good in monochromatic condition
   Disadvantage: limited FOV(angle selected) ; Color non uniformity
4) Curved mirror and free shape optics
   a. Olympus Optics(free form prism ,PC Eye-Trek/AR walker/MEG4.0)
   b. Augmented Vision(Prof. Hong Hua Free form lens)
   c. LASTER Technologies(curved semi-reflection)
5) Projection
   a. Microvision PicoP HUD
   b. Penny Interactive Glasses BM20
   c. NEC Tele Scouter/Brother AiRScouter
   d. GlassUp
   e. Innovega iOptik(project real image onto glass and wear a contact lens to see the focused image)

f. Telepathy(micro projector)
g. Fujitsu Laser Head Set (laser project)
h. Avegant's Virtual Retinal Display projects

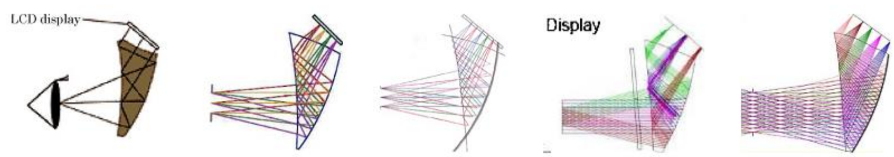
6) Others:
a. Synopsys/ Optical Research Associates
b. Fraunhofer COMEDD(OLED)
c. NTT DOCOMO AR Glasses
d. Laster EyePhone
e. OmniVision(liquid crystals on silicon to display)
f. Skully helmet (AR helmet)

2. Aim of the project and technical specification

The aim of this project will be design a lightweight, compact see-through head mount display device with large FOV and small f/#

There are several Existing HMD designs using the FFS Prism technology[2]

Table 1. Specifications of Some Existing HMD Products that Use the FFS Prism Technique



	Eye-Trek FMD 220	Z800 3dvisor	*i* Visor	ProView SL40	Our Design
Module view					
Full diagonal FOV (°)	37	39.5	42	40	53.5
Eye relief (mm)	23	27	22	30	18.25
Exit pupil diameter (mm)	4	4	3	5	8
Effective focal length (mm)	21	22	26.7	20.6	15
Diagonal image size (in.)	0.55	0.61	0.81 [a]	0.59	0.61
f/#	5.25	5.5	8.9	4.1	1.875

[a]The size is calculated from the FOV and EFL.

Table 1.Specification of the display system

Specification	Parameter	Explanation
Dia FOV	30deg-50deg	
Size	No large than 25mm*22mm*12mm	
Eye relief	18mm-30mm	
Exit pupil	>4mm	Human pupil 4-8mm
f/#	<5	

Table 2. Specification of the Microdisply(eMargin VGA)

Parameter	Specification
Format	640 (x3) x 480 pixels
Total Pixel Array	680 (x3) x 520 pixels
Color Pixel Aspect Ratio	15 micron square color group
Color Pixel Arrangement	R, G, B Vertical Stripe
Display Area	10.02 x 7.80 mm (12.84 mm diagonal, 0.50”)
Useable Display Area	9.6 x 7.2 mm (12.0 mm diagonal, 0.47”)
Mechanical Envelope	16.5 x 18 x 5.01 mm (rigid carrier board)
Weight	~ 2 grams
White Luminance (Color display)	⩾ 150 cd/m2 (front luminance), VGA 60Hz VESA mode

3. Major techniques and reference

The Major techniques will be the free form optical elements design.

The important reference will be the research from Morishima *et al.*[3], Inoguchiet al.[4], Hoshiet al[5], Yamazaki et al.[6] and Hua et al[2].

4. About freeform design:

a. What is freeform design?

A freeform surface normally defined as the surface which is not rotational symmetric. Compared with the conventional optics, these surfaces provide additional degrees of freedom that can lead to improved performance. [7]

b. Why freeform design, what is the benefits?

The optical system including freeform elements have the opportunities for numerous improvement in performance. Such as fast optics, more compace packing.[7]

1) With freeform optics, the system could be accomplished with less optics which will lead to less light loss because of the interaction with the surfaces.
2) Less optics all cause small mass and size
3) Freefrom optics can also improve optical quality with the correction of spherical aberration and coma and distortion
4) More favourable position of the optical components is possible

c. How to do freeform design?

There are there main ways to describe freeform surfaces. For example NURBS,XY polynomial and radial basis function representation.

Fig1 shows the block diagram of freefrom engineering. SPDT is single point diamond turning.

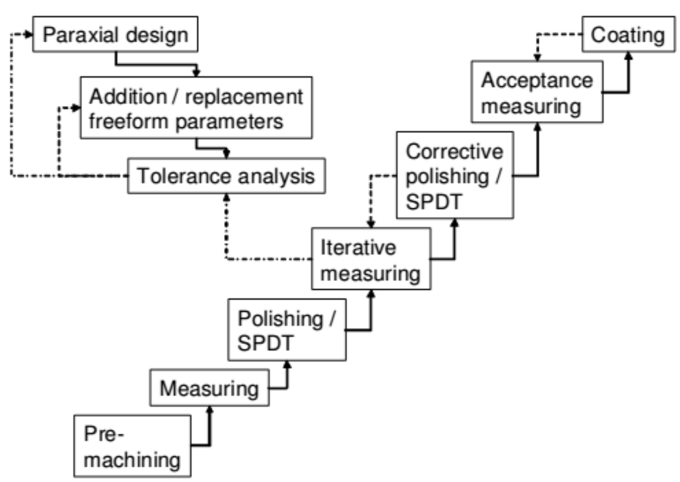


Fig1. Design and fabrication flow of non-conventional optics

d. How to fabricate the freeform design?

Diamond turning machine.

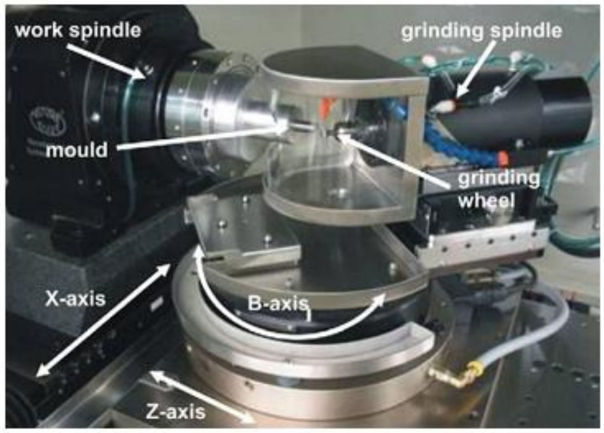


Figure 2 Wheel normal grinding[8]

Table 3 shows the comparison of current asphere tolerance limits to freeform tolerance limits.

Attribute	Asphere Tolerancing Limit	Freeform Tolerancing Limit
Glass Quality (n_d, v_d)	Melt Rebalanced and Controlled	Melt Rebalanced and Controlled
Diameter (mm)	+0, -0.010	+0, -0.010
Center Thickness (mm)	± 0.010	± 0.050
Clear Aperture	100%	100%
Vertex Radius	± 0.1% or 3 HeNe fringes	NA
Irregularity – Interferometry (HeNe fringes)	0.05	0.1 (Stitching/CGH dependent)
Irregularity – Profilometry (µm)	± 0.5	± 1.0
Wedge Lens – ETD (mm)	0.002	TBD
Bevels – Face Width @ 45° (mm)	± 0.05	± 0.05
Scratch – Dig (MIL-PRF-13830B)	10 – 5	10 – 5
Surface Roughness (Å RMS)	10	10

Table 1 General list of soft tolerance limits for glass aspheric and freeform optics[8]

e. Where to get it fabricated?

UA_OSC

University of Rochester-Center for freeform optics

Luzerne Optical- ZEISS PERSONALIZED LENSES[9]

5. Start point of the free form surface prism OST-HMD

Use the Patent 5959780 example 1 as a starting point.This prism design consists of two freeform surfaces and one planer surface.Based on a 1.3 in microdisplay, the design offers a full FOV of the system that is 57.8degre*36.6degree with an exit pupil diameter of 4 mm and The effective focal length is about 27.4mm. The f –number is 6.85. [10]

The parameter of the design is:

Surface No.		Radius of curvature	Surface separation	Refractive index (Eccentricity)	Abbe's No. (Tilt angle)
1		∞ (pupil)			
2	R_y	−209.268		1.4922	57.50
(first	R_x	−95.115		(from pupil position)	
surface)	K_y	0		Y −18.335	θ −12°
	K_x	0		Z 27.921	
	R_2	7.8387×10^{-7}			
	R_3	2.9947×10^{-13}			
	R_4	1.5297×10^{-14}			
	R_5	-5.0289×10^{-17}			
	P_2	−0.4499			
	P_3	−7.9471			
	P_4	0.6545			
	P_5	−0.1387			
3	R_y	−67.801		1.4922	57.50
(second	R_x	−58.220		(from pupil position)	
surface)	K_y	0		Y 9.356	θ 27.44°
(reflecting	K_x	0		Z 38.348	
surface)	R_2	4.2705×10^{-7}			
	R_3	-7.7029×10^{-11}			
	R_4	4.0793×10^{-22}			
	R_5	1.0591×10^{-17}			
	P_2	0.1070			
	P_3	0.4967			
	P_4	119.38			
	P_5	−0. 0092			
4	R_y	−209.268		1.4922	57.50
(first	R_x	−95.115		(from pupil position)	
surface)	K_y	0		Y −18.335	θ −12°
(reflecting	K_x	0		Z 27.921	
surface)	R_2	7.8387×10^{-7}			
	R_3	2.9947×10^{-13}			
	R_4	1.5297×10^{-14}			
	R_5	-5.0289×10^{-17}			
	P_2	−0.4499			
	P_3	−7.9471			
	P_4	0.6545			
	P_5	−0.1387			
5		∞		(from pupil position)	
(third				Y −27.164	θ −62.56°
surface)				Z 27.921	
6		∞		(from pupil position)	
(display plane)				Y −27.678	θ −46.89°
				Z 39.000	

Use the CodeV sequential surface to model the design. It is unnecessary to use NSS design here, even the light will interact with the first surface twice. It is still completely sequential. The trick here is set the surface 4 have exact same parameter with surface 2. Use pickup here for this configuration.

The following section is the step-by-step procedure.

1) Then change the surface parameters based on the design data above. Take surface 1 for example: Change the surface type from spherical to anamorphic asphere.
   Then change the aspherical coefficients in the *Surface Properties*:
   Compare the aspherical setup in the pattern which is

$$z = \frac{C_X x^2 + C_Y y^2}{1 + \sqrt{1 - (1 + k_x) C_X^2 x^2 - \left(1 + k_y\right) C_Y^2 y^2}} + \sum_{n=2} R_n \left((1 - P_n) x^2 + (1 + P_n) y^2\right)^n$$

   with the CodeV setup:

$$\mathrm{z} = \frac{(\mathrm{C_{UX}}) x^2 + (C_{UY}) y^2}{1 + \sqrt{1 - (1 + k_x)(C_{UX})^2 x^2 - \left(1 + k_y\right)(C_{UY})^2 y^2}} + AR\left((1 - AP) x^2 + (1 + AP) y^2\right)^2$$
$$+ BR\left((1 - BP) x^2 + (1 + BP) y^2\right)^3 + CR\left((1 - CP) x^2 + (1 + CP) y^2\right)^4$$
$$+ DR\left((1 - DP) x^2 + (1 + DP) y^2\right)^5$$

   AR,BR,CR,DR are the rotationally symmetric portion of the 4th,6th ,8th and 10th order deformation from the conic. AP,BP,CP,DP represent the non-rotationally symmetric components of the 4th,6th ,8th, 10th order deformation from the conic.
   In this sense, we got the counterpart:

Symmetric	R_2	AR	4th
	R_3	BR	6th
	R_4	CR	8th
	R_5	DR	10th
Non-symmetric	P_2	AP	4th
	P_3	BP	6th
	P_4	CP	8th
	P_5	DP	10th

2) For decenter and tilt setup of stop and surface 2-5, use the 'Global coordinates' for the decenter type. For image plane, use the 'decenter and return' for the decenter type. So,

$$\Delta \mathrm{Y} = (-27.678) - (-27.164) = 27.164 - 27.678 = -0.514$$
$$\Delta \mathrm{Z} = 39.00 - 27.921 = 11.079$$
$$\Delta \theta = -46.89 - (-62.56) = 15.67$$

3) The patent use optical material with refractive index as 1.4922, and Abbe number is 57.5. here choose optical plastic PMMA with refractive index 1.4813 and Abbe number is 52.60
4) After change all of the parameters the system data is

System Data... Surface Properties...

Surface #	Surface Name	Surface Type	Y Radius	X Radius	Thickness	Glass 1	Glass 2	Refract Mode	Y Semi-Aperture	Non-Centered Data
Object		Sphere	Infinity	Infinity	Infinity			Refract	O	
Stop		Sphere	Infinity	Infinity	0.0000			Refract	2.0000 O	
2		Anamorphic	-209.2680	-95.1150	0.0000	PMMA_SPE		Refract	26.1632 O	Global Coordinates
3		Anamorphic	-67.8010	-58.2200	0.0000	PMMA_SPE		Reflect	20.0786 O	Global Coordinates
4		Anamorphic P	-209.2680 P	-95.1150 P	0.0000	PMMA_SPE	AIR	Only TIR	18.0056 O	Global Coordinates
5		Sphere	Infinity	Infinity	0.0000			Refract	15.2027 O	Global Coordinates
Image		Sphere	Infinity	Infinity	0.0000			Refract	15.9514 O	Decenter & Return

End Of Data

5) Lay out the system, set up the surface drawing with only 'show only used area of the surface'

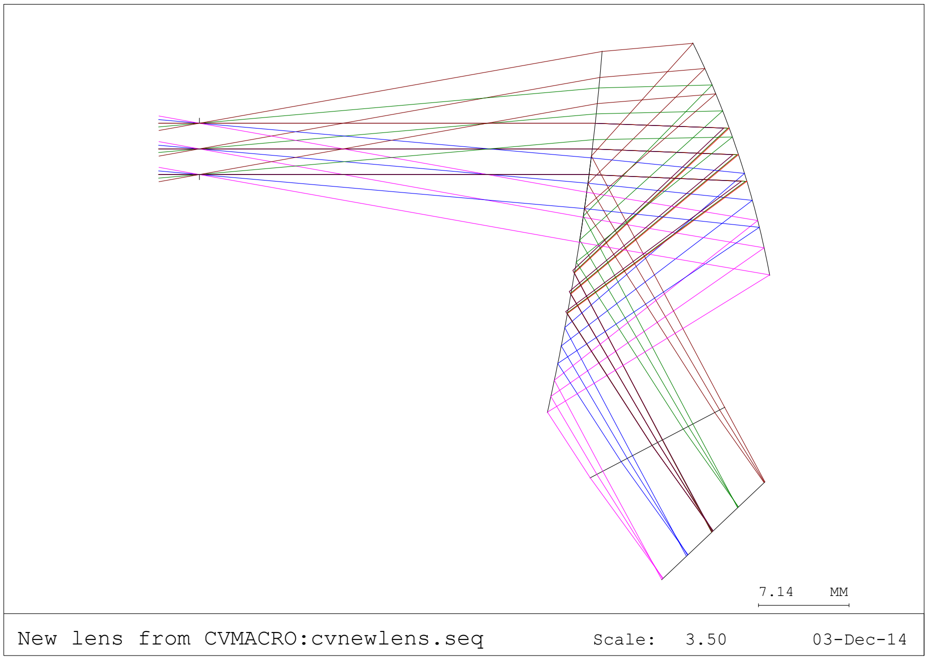


Figure 3 start point layout

6) Scale the system for EFL around 15mm, increase the exit pupil into 8mm dia. Increase the FOV into [-9,15].
7) After scale the system and increase the exit pupil size, there is large vignetting for the initial setup, need to set vignetting or the valid start point.
The following figure 4 is system with vignetting. Figure 5 shows the MTF for this system.

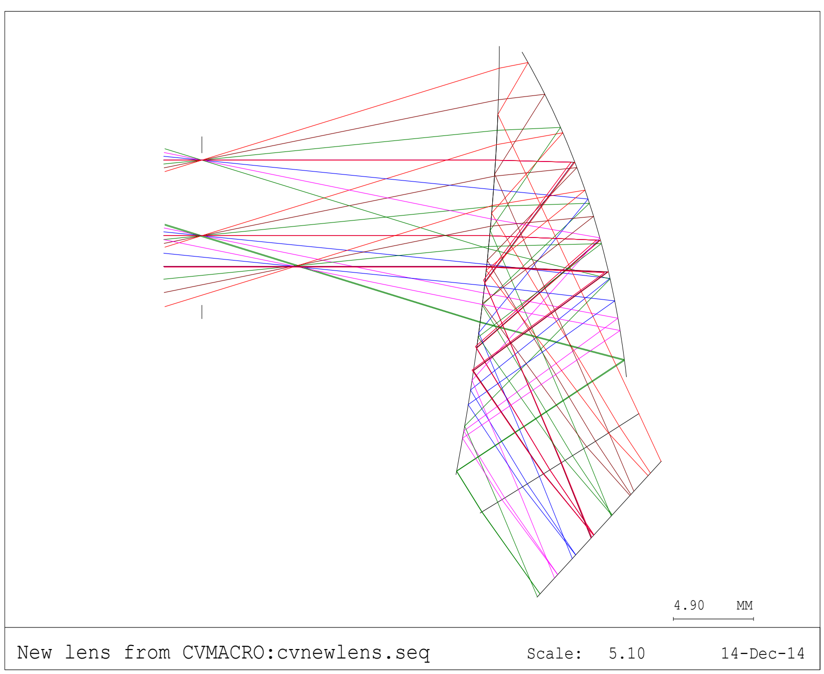


Figure 4. Start point system with 4mm diameter exit pupil and 15mm EFL

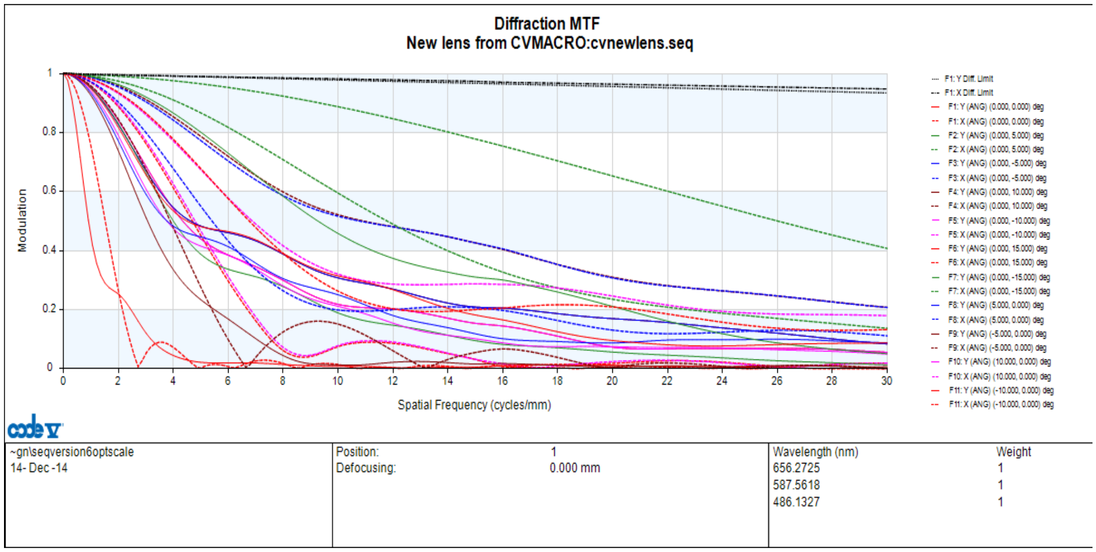


Figure 5. MTF for start point system with vignetting

6. Optimization

The spectrum of the OLED microdisplay:

Table 4. optimization wavelength setup

Wavelength	Weights
486.1nm	1
546.1nm	1
587.6nm	2
656.3nm	1

- **Constrains [2]**

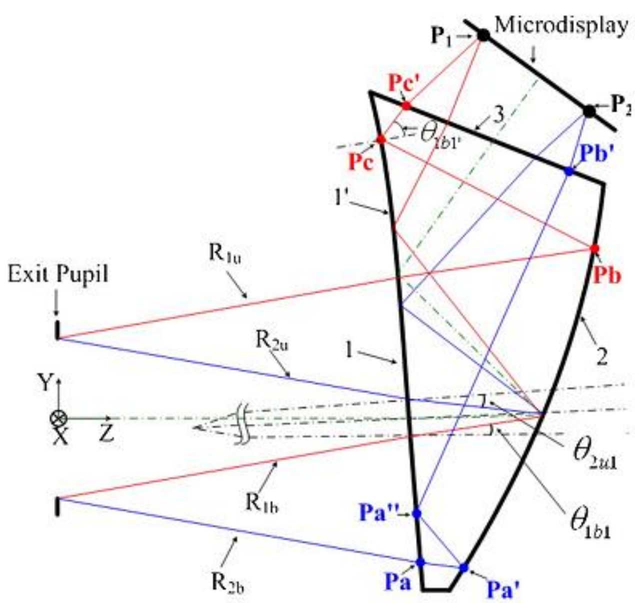


Figure 6. Free form prism

Table5.constraits and CODEV command

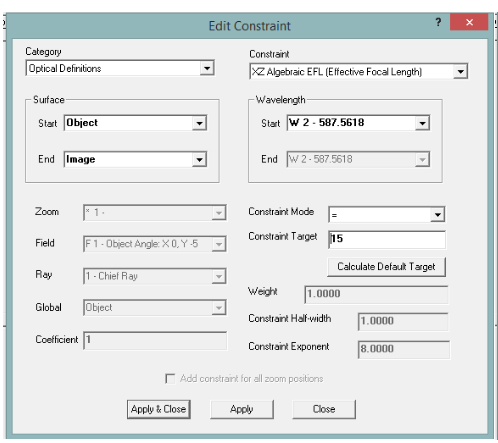
Class	Constrains	In CODEV
TIR	$\theta_{1b1'} > \arcsin(1/n)$	AOI R3 S4 W2 F5 Z1 > 42.14
Structure Constraints	$y_{Pa'} - y_{Pa} < 0;$ $y_{Pa''} - y_{Pa} > 0$ $0.5 < z_{Pa'} - z_{Pa} < 2$	Y R2 S2 W2 G1 F4 Z1 < 9 Y R2 S2 W2 G1 F4 Z1 > 4 Y R2 S3 W2 G1 F4 Z1 > 9 Y R2 S4 W2 G1 F4 Z1 > 0 Y R2 S4 W2 G1 F4 Z1 < 3 Z R2 S2 W2 G1 F4 Z1 < 33 Z R2 S2 W2 G1 F4 Z1 > 32
Structure Constraints	$y_{Pb'} - y_{Pb} > 0$ $-1.5 < z_{Pb'} - z_{Pb} < -0.2$	Z R2 S3 W2 G1 F4 Z1 > 37 Z R2 S3 W2 G1 F4 Z1 < 38 Y R3 S3 W2 G1 F5 Z1 > -13 Z R3 S3 W2 G1 F5 Z1 > 44.8 Z R2 S5 W2 G1 F4 Z1 < 44.6 Y R2 S5 W2 G1 F4 Z1 < -15
Structure Constraints	$-2 < y_{Pc} - y_{Pc'} \le 0$ $0 < z_{Pc} - z_{Pc'} < 1$	Y R3 S4 W2 F5 Z1 < -2 Z R3 S4 W2 F5 Z1 < 0 Z R3 S4 W2 F5 Z1 > -1 Y R3 S5 W2 F5 Z1 > 0
Structure Constraints	$z_{pa} \ge 17$ $z_{pc} \ge 17$	Z R2 S2 W2 G1 F4 Z1 > 17 Z R3 S4 W2 G1 F5 Z1 > 17
Effective focal length	EFLx = 15mm-+5mm	FPX S1..5 W2 Z1 < 17 FPX S1..I W2 Z1 > 14
Effective focal length	EFLy = 15mm-+5mm	FPY S1..5 W2 Z1 < 17 FPY S1..I W2 Z1 > 14

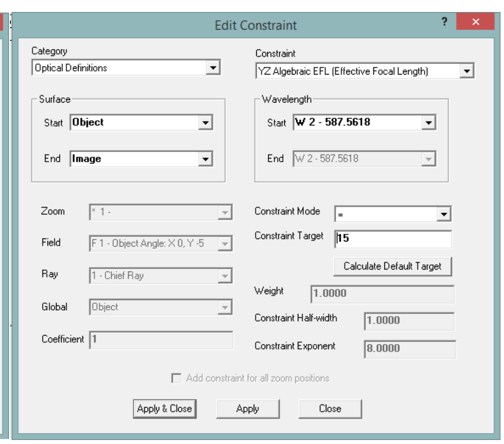
Take EFL constraints setup and TIR constraint setup for example:

- Constraints 1:

EFLx=15mm;EFLy=15mm;

Use real ray tracing constraints as showed in the following figures:



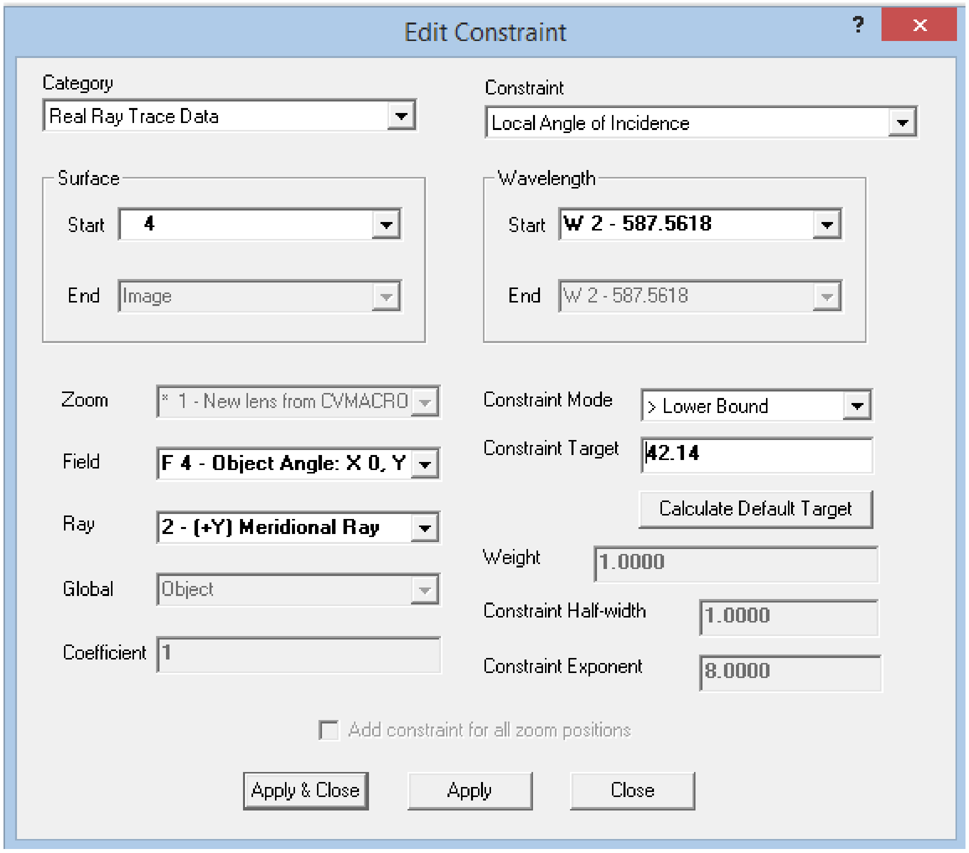


- Constraints2:

TIR: Since use PMMA, the refractive index is n=1.4906 at wavelength=587nm;

$$\theta > \arcsin\left(\frac{1}{n}\right) = \arcsin\left(\frac{1}{1.4906}\right) = 42.1343°$$

Find out the smallest incident angle of the TIR surface which is surface 4, it is the X=0,Y=10, marginal ray have the smallest angle.



- **Variables**
  a) All the primary curvatures of all surfaces in both the tangential and sagittal planes
  b) Aspherical coefficients
  c) Decenter in both Y and Z directions
  d) Tilt about the X axis
  e) The height of the rays striking the image plane(in order to control the distortion)
- **Optimization strategy**
  1) For FOV,gradually increasing the field samples as the system performance improves during the optimization process instead of a densely sampled grid across the entire FOV.
  2) The tilt and decenter parameters were set as variables in the entire optimization processing.
  3) Use spherical surface first to find out the first order geometrical parameter.Then change to aspherical surface for optimization.Then convert ASP to AAS (anamorphic aspherical) up to 10th order variables. Then convert AAS to XYP for global optimization.
  4) Finish the optimization for y field first, then expand the x field for optimization.
- **Optimization result:**
  Figure 7 shows the design result of the free form prism.

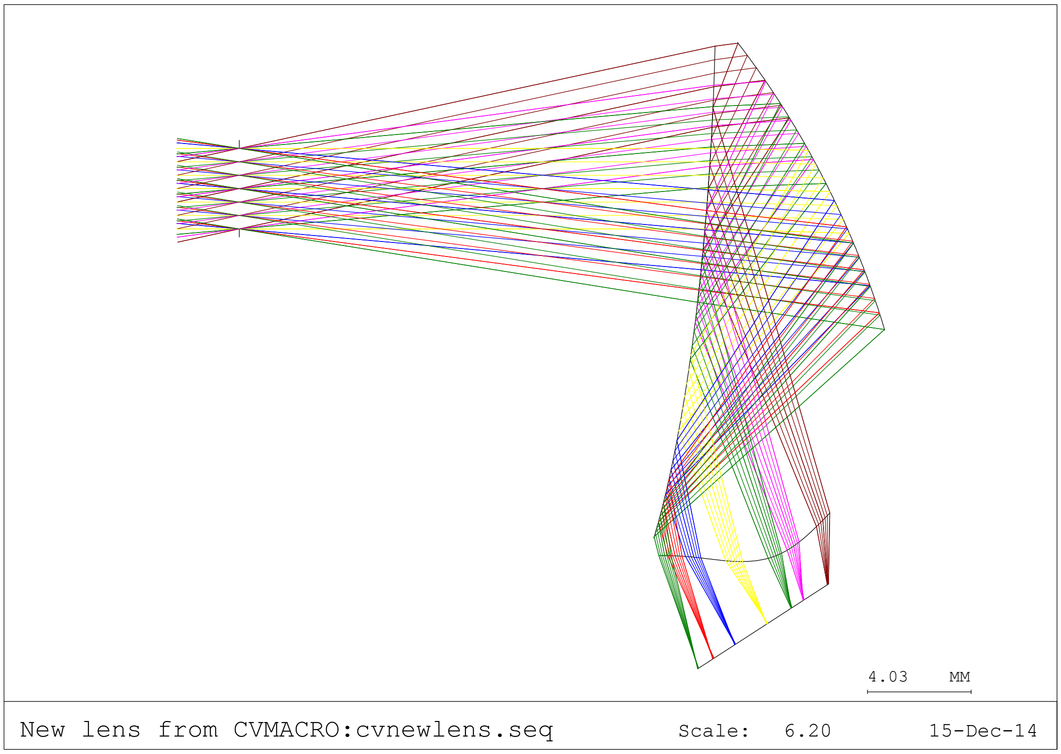


Figure7. Design result

Figure 8 shows the MTF for the design. Compared with the start point MTF, the MTF have a lot improvements.

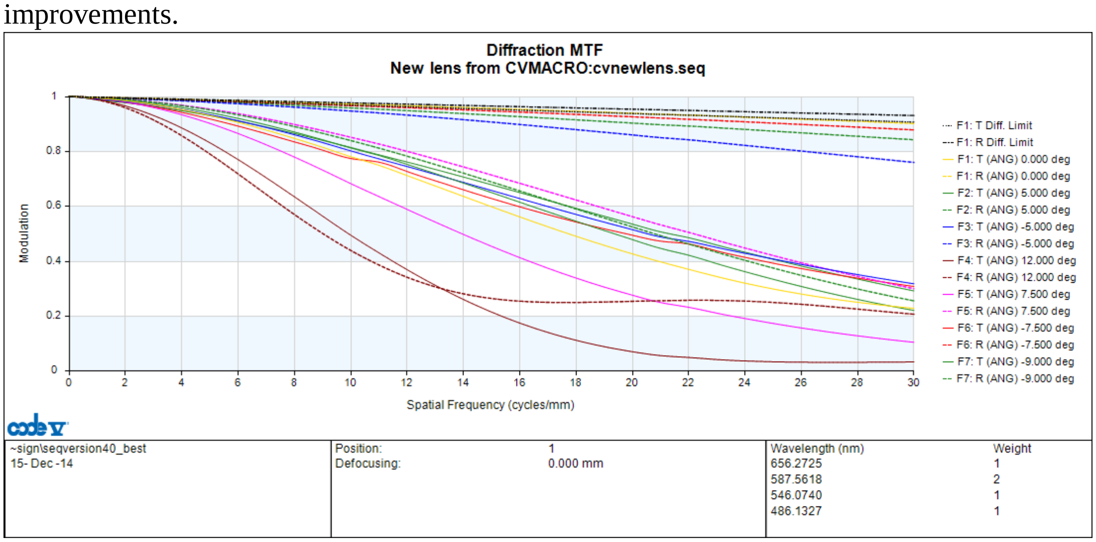


Figure7. MTF of the design result

Figure 8 shows the ray aberration for the design.

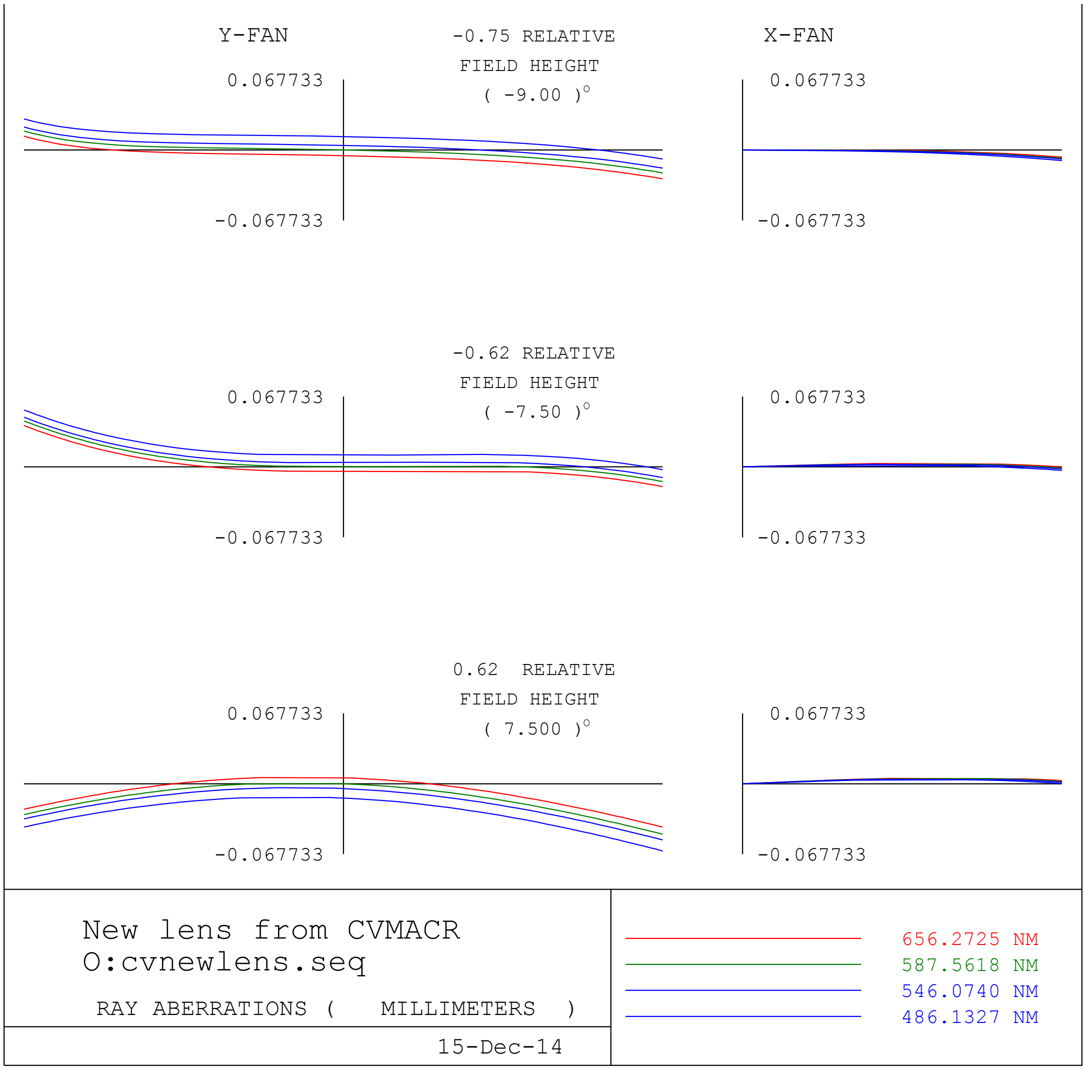


Figure8. Ray aberration of the design result

Table 6 shows the specification requirement and the design specification. There is still large space for the FOV improvement.

Table 6. Specification

Specification	Requirement	Design
Dia FOV	30deg-50deg	21deg*10deg
Size	No large than 25mm*22mm*12mm	21mm*12mm for YOZ
Eye relief	18mm-30mm	18.7mm
EFL	Around 15mm	around 6mm
Exit pupil	>=8mm	8mm
f/#	<5	1.927

- **Auxiliary Free-form lens design:**

The freeform prism with curved surfaces produces optical power in the optical see-through path,causing a significant viewing axis deviation and undesirable distortion as well as other off-axis aberrations to the view of the real-world scene. An auxiliary lens is required not only to cancel the optical power in the see-through path but also to correct the deviation of the optical axis and the off-axis aberrations introduced by the FFS prism.

Figure 9 shows the auxiliary free from lens design result. Together with the free from prism this system should be an afocal system.

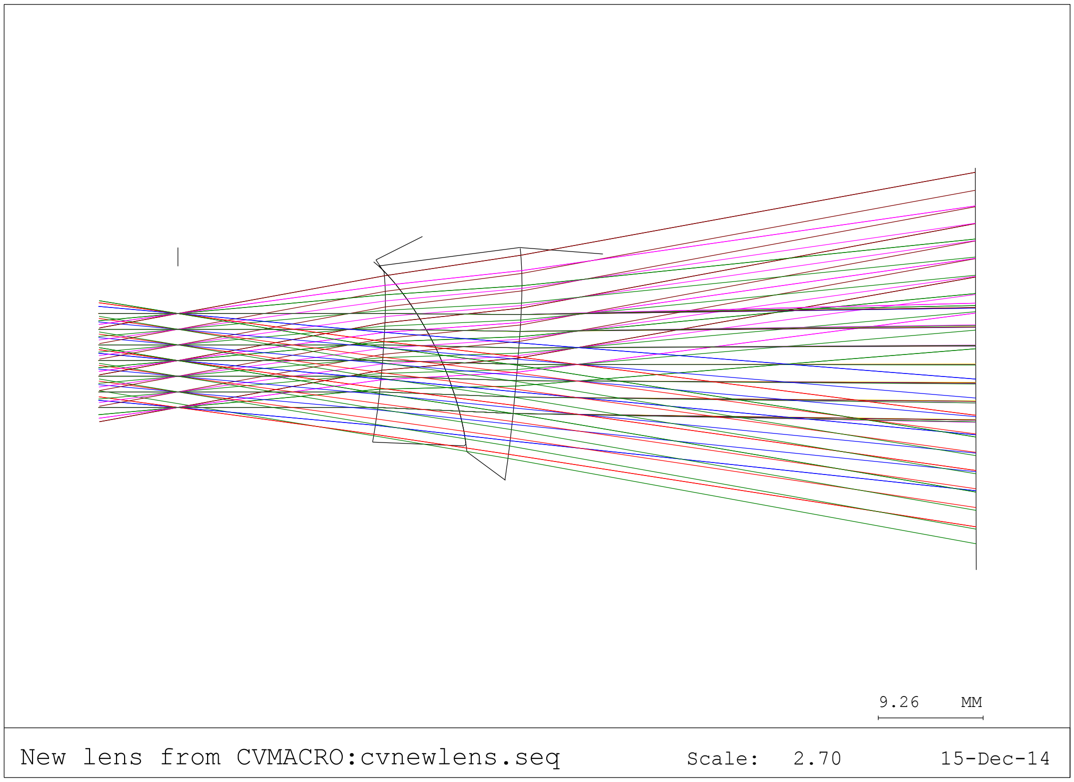


Figure 9. Auxiliary free from lens with free from prism

Reference:

[1] "Head Mounted Display Market -Global Industry Analysis, Size, Share, Growth, Trends and Forecast, 2013- 2019".

[2] Dewen Cheng, Yongtian Wang, Hong Hua, and M. M. Talha. Design of an optical see-through head-mounted display with a low f-number and large field of view using a freeform prism. Appl. Opt., 48(14):2655–2668,2009.

[3] H. Morishima, T. Akiyama, N. Nanba, and T. Tanaka,"The design of off-axial optical system consisting of aspherical mirrors without rotational symmetry," in 20th Optical Symposium,Extended Abstracts(1995), Vol. 21, pp. 53–56.

[4] K. Inoguchi, H. Morishima, N. Nanaba, S. Takeshita, andY. Yamazaki,“Fabrication and evaluation of HMD optical system consisting of aspherical mirrors without rotation symmetry,”inJapan Optics’95, Extended Abstracts(1995), pp. 19–20

[5] K. Takahashi,“Image display apparatus comprising an internally reflecting ocular optical system,” U.S. patent5,699,194 (16 December 1997).

[6] H. Hoshi, N. Taniguchi, H. Morishima, T. Akiyama, S. Yamazaki, and A. Okuyama,“Off-axial HMD optical system consisting of aspherical surfaces without rotational symmetry,”Proc.SPIE2653, 234–242 (1996).

[7] M. D. Nijkerk, O. E. van der Togt-Marinescu, G. P. H. Gubbels. FREEFORM DESIGN AND FABRICATION: WHERE THE PROOF OF THE PUDDING IS IN VERIFICATION

[8] F.Z. Fang , X.D. Zhang. Manufacturing and measurement of freeform optics

[9] http://www.luzerneoptical.com/top-wholesale-optical-labs/new-products/freeform-lens-free-form-lenses/zeiss-personalized-freeform-lens.html?sl=EN

[10]Patent 5959780