3D Plenoptic Microscope System

Design Description Document

3D Team: Nightingale

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Revision History

Rev.	Date	Comments
1	January 23, 2017	Initial revision
2	February 6, 2017	Add objective and initial Rayleigh design
3	February 17, 2017	Add 3 optimized designs, each including objective, relay, and tube lens Add specification table
4	February 27, 2017	Reorganize the DDD, provided more details including design process and explanation for system design as a whole, objective, relay, and tube lens.
5	April 3, 2017	Add Micro Lens Array into the system; add tolerancing results; add filter into the system.
6	April 25, 2017	Add image reconstruction algorithms

Table of Contents

Introduction

Light-field (plenoptic) cameras can capture both spatial and angular information, which can be reconstructed to form an image with depth information using additional software. Since a single capture is sufficient, a plenoptic camera requires less time to capture 3D images than a traditional, manual approach. This makes a plenoptic camera suitable for industrial inspection.

This senior design project is a collaboration with Navitar, Inc., a manufacturer of optical systems who focuses on designing, developing, manufacturing and distributing precision optical solutions across the globe.

Project Nightingale is an apochromatic, plenoptic microscope with high-resolution 3D reconstruction capabilities and a long working distance. One application of this plenoptic camera is the inspection of microelectronic components on assembly lines. To serve this purpose, this plenoptic system will consist of five components: an objective lens, a tube lens, a relay stage, a micro-lens array, and a sensor, as illustrated in Figure 4.

System Overview

This system's lens design contains three stages: an objective lens, a tube lens, and a relay stage, as well as a micro-lens array and a sensor, as illustrated in Figure 4. Please note that the model in CodeV is flipped left to right.

The objective serves to collimate the light bundle from the object. It contains the first four elements in the system. The aperture stop is controlled to be 5mm away from the object to ensure easier access and a cost-effective opto-mechanical scheme.

The afocal relay system consists of the next three elements after the objective. It images the aperture stop away from the objective to the object space. This is needed to shorten the overall length of the system, as the final system needs to fit in the mounting of an existing product of the company, shown in figure 3. The afocal relay in this design has a 1x magnification, which is a placeholder for the existing zoom relays in the company's product line.

The tube lens is the doublet after the afocal relay. The effective focal length (EFL) of the tube lens is two times of the EFL of the objective to form a 2x magnification system. The front focal point of the tube lens is controlled to coincide with the pupil imaged by the afocal relay. This design ensures a high-quality image-space telecentricity for the plenoptic camera design.

As an industrial inspection device, the system needs to survive in -40 °C to 70 °C and operate at room temperature with no significant change in performance across normal room temperatures.

Figure 1. System Illustration. A current product that has a similar layout and dimensions as the product we are designing.

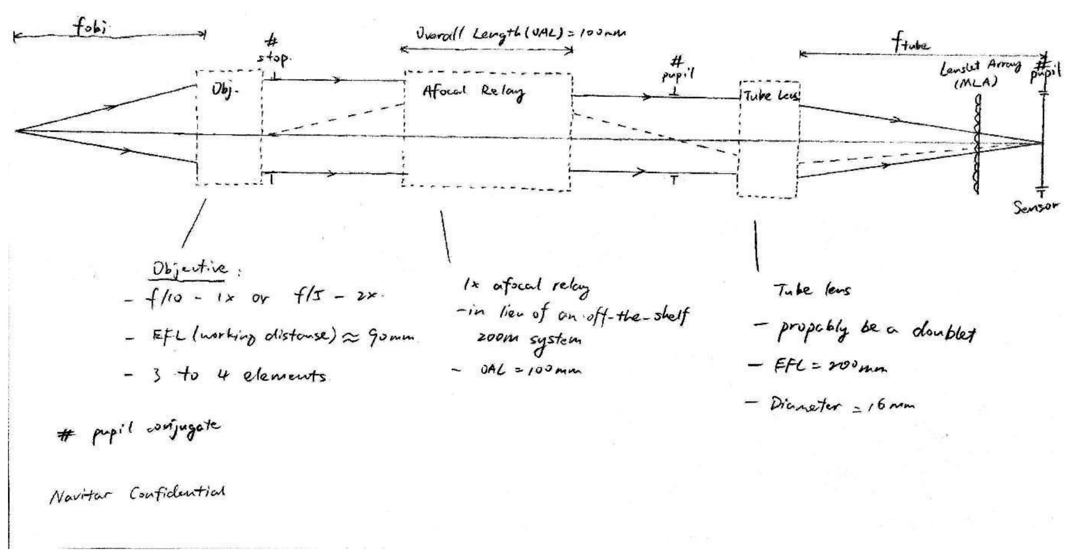

Figure 2. Plenoptic System Sketch.

Details of Design

This section includes the layout of the design, the specification table, and analysis of the design for the system as a whole, as well as the interpretation of the objective lens, relay lens system, and the tube lens.

The following layout is an overview of the system. The sensor is on the right of the system. Starting from the sensor and going along the optical path from right to left, the first doublet serves as the tube lens, the following three elements serve as the relay lens system, and the remaining two singlets and the doublet after the aperture stop serve as the objective.

All the performance and tolerancing results are for the system without the Micro Lens Array. The filter near the aperture stop is a IR filter made of 1 mm thick SBSL7_OHARA.

Figure 3. Lens Display of Design

Table 1. System specifications.

Specification	Requirements	Design Performance
Magnification	~~1x or~~ 2x	2X
Wavelength	450nm, 550nm, 650nm	450nm, 550nm, 650nm
Working distance	90 mm	90mm
Field of View	8mm diagonal object space	8mm diagonal object space
Total Length	422.5 mm	418.99 mm
Objective F/#	~~10 (1x)~~ 5 (2x)	5 (2x)
Image Format	1” (4K compatible)	1” (4K compatible)
Number of pixels	4096 x 2160	4096 x 2160
Sensor size	14.13 x 7.51 mm	14.13 x 7.51 mm
Pixel size	3.45 µm	3.45 µm
Image Circle (nominal)	16 mm diameter	16 mm diameter
Distortion	<0.25%	0.17%
Relative Illumination	>85%	>98.82% across all field
Design MTF	>40% across all fields at 72.5 lp/mm	>43.3% across all fields at 72.5 lp/mm
Telecentricity	In sensor space	In sensor space
IR Filter	Included	Included
Plenoptic Type	Plenoptic 1.0 (pupil relay type)	Plenoptic 1.0 (pupil relay type)
Plenoptic Micro Lens Array	Details in Following Content	Details in Following Content

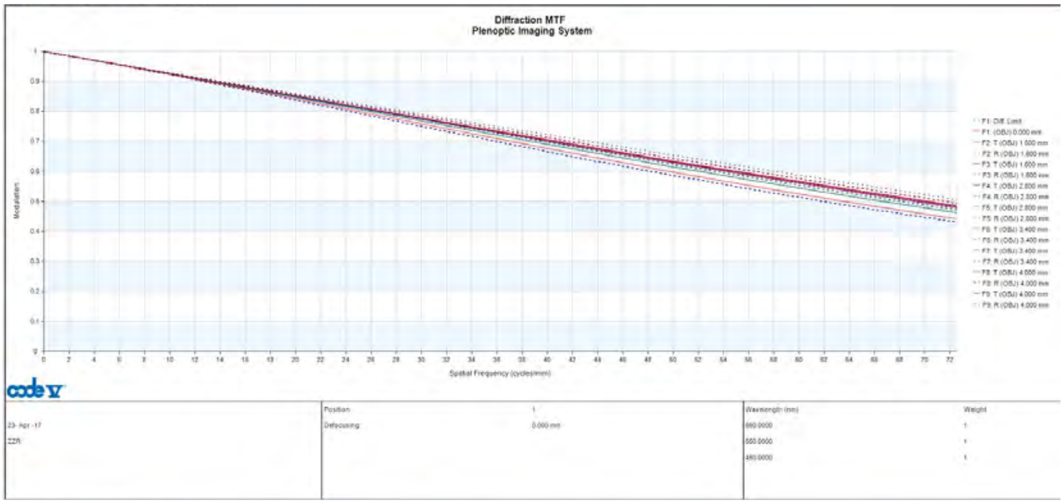

Figure 4: MTF chart of the system. The requirement for MTF is >40% at 72.5 lp/mm for all fields. The design has the lowest MTF at full field at 43.3% at 72.5lp/mm, very close to diffraction limit.

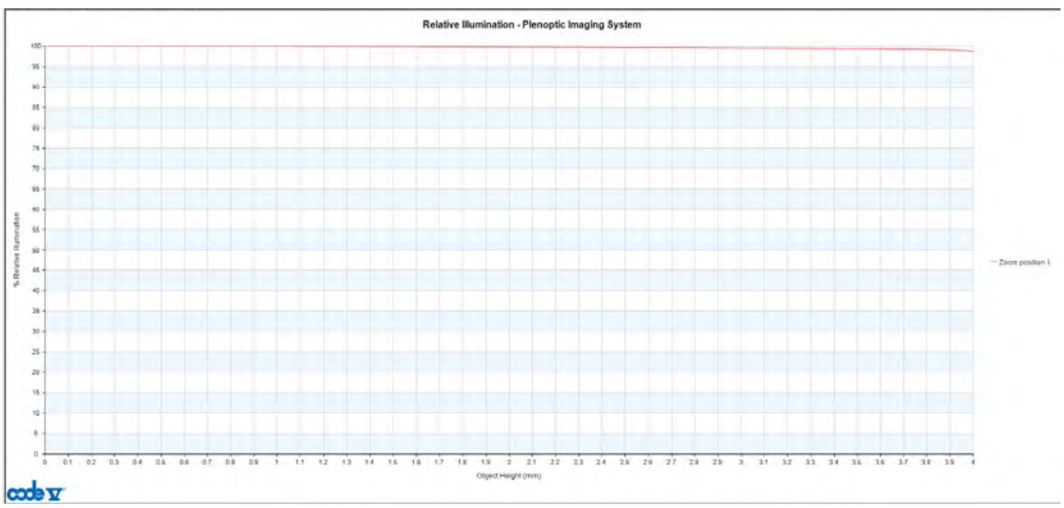

Figure 5: Relative illumination. The requirement for relative illumination is >85% across all field. With very low vignetting, the design keeps the relative illumination higher than 98.82% across all fields.

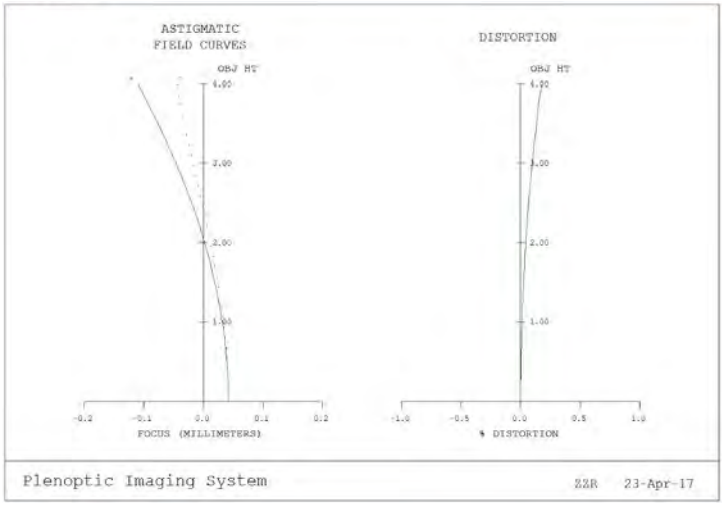

Figure 6: Field curves. In this design, the distortion is less than 0.17%.

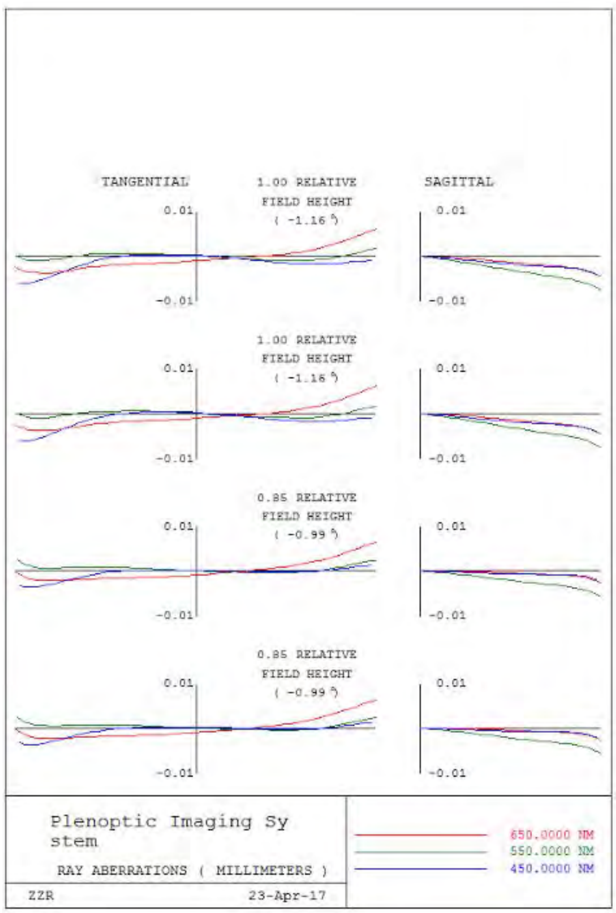

Figure 7: The aberration plot over all field at 450, 550 and 650mm wavelength. At the scale of 0.005 aberration/inch, the plot shows the color is well corrected, and that the design is limited by higher order aberrations.

Objective

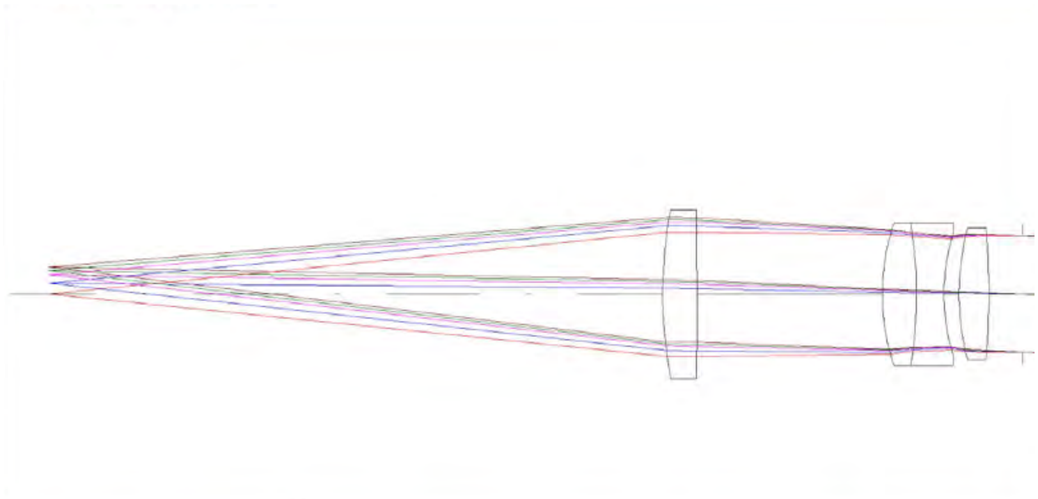

Figure 8: Drawing of the objective.

The objective for the system contains two positive singlets and one negative doublet in the middle. The effective focal length of the objective is 95mm. The design is generated from a cooke triplet and optimized by replacing the middle singlet with a doublet to correct for chromatic aberrations while satisfying the effective focal length requirement.

The original design for the objective was a singlet followed by a triplet. It has been replaced because of the difficulty to manufacture a triplet and because of its high angles of incidence and refraction . The original design is attached in Appendix C.

Relay

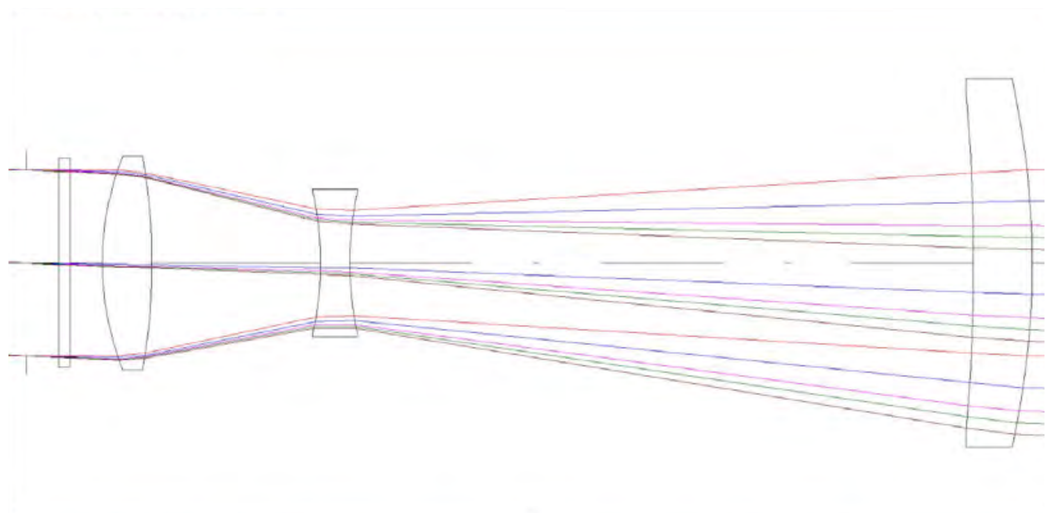

Figure 9: Relay Lens System Design with Infrared Filter

The afocal relay consists of three elements, with the first having positive power, the middle element having negative power, and the last having positive power. It images the exit pupil of the objective to some distance away from the objective across the system. It is a placeholder for a zoom lens system that is not part of this design. Since the objective is infinity-corrected, this relay is afocal. In the CodeV model shown above, the relay is designed with a 95mm-EFL perfect objective.

The other relay design used two singlets with a doublet in the middle. It has been replaced with due to unfavorable performance while working with the rest of the system. The original design is attached in Appendix C.

Tube Lens

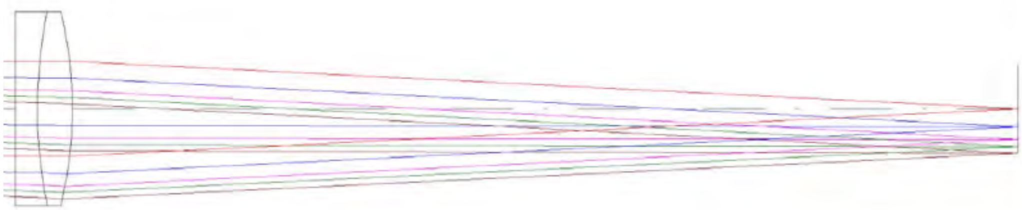

Figure 10. Tube Lens System Design

The tube lens is located between the relay and the micro-lens array. It takes the collimated rays from the relay and focus them to an image on the sensor plane. To form a 2x magnification system, the EFL of the tube lens is 190mm. The tube lens also relays the exit pupil of the system to infinity, making the system telecentric in image space. We use one doublet as tube lens as it is sufficient in color correction.

Tolerancing

Tolerancing tests are done with the tolerancing spec from Navitar. Specific numbers are listed in the Appendix.D. The result is shown in Figure 11.

In the tolerancing test, the system can achieve about 40% probability in meeting the nominal performance spec. However, Navitar has confirmed with us that since the performance spec is not for the final plenoptic images, they accept this tolerancing result.

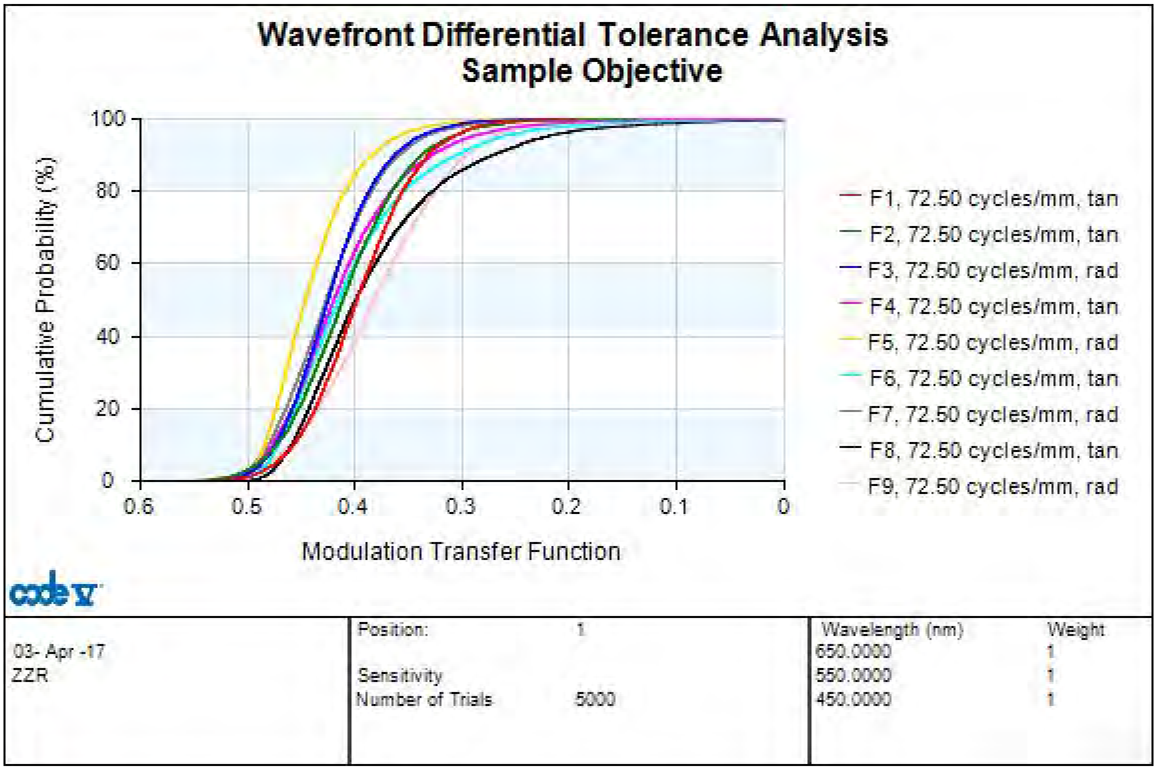

Figure 11: Tolerancing results. The MTF spec is evaluated at 0.4.

Micro Lens Array

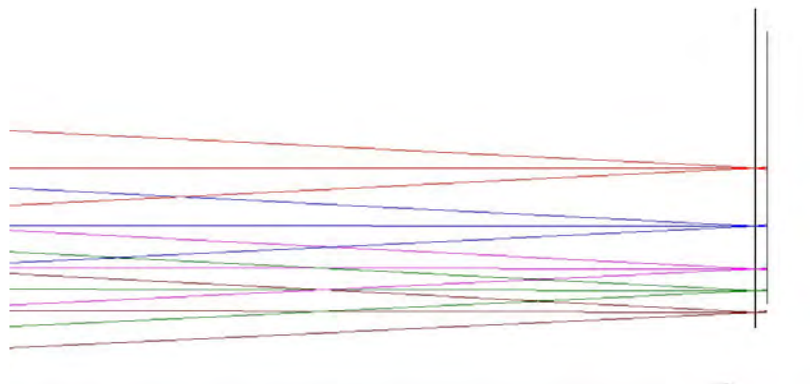

Figure 12: The MLA in CodeV

Surface Property:

Material: NBK7

User Defined Surface Type: cv_umr:cv_uds_flyseye.dll

Y Radius: 0.0897mm (second surface convex).

C1: X interval in array: 0.00345055

C2: Y interval in array 0.00345055

Resolution Calculation:

The spec of our sensor is listed below:

Imager Format: 1” (4K compatible)

Number of pixels: 4096 x 2160

Sensor size: 14.13 x 7.51 mm

Pixel size: 3.45 μm

The MLA has 819 x 432 lenslets with 5 x 5 pixel size each.

The pitch of the microlens array will need to be:

sensor size/ number of pixels = 14.13 mm / (819 x 5 pixels) = 3.45055μm

In a paper from Lytro [Ren el al. 2005, https://graphics.stanford.edu/papers/lfcamera/lfcamera-150dpi.pdf], the F-number of the lenslets needs to match that of the main lens, so the microlens array should have lenslet with aperture of f/10.

With the pitch of the microlens array, which is also the diameter of the lenslet, we can get the focal length of the lenslet:

focal_length = pitch size * f_number = 3.45055 μm * 10 = 34.5055 μm

Manufacturer:

Due to the small size of our micro lens array in this design, it does not exist in the current catalog of the manufacturers in market. Newport, Edmund, Thorlabs are not able to provide such products due to the long focal length. The team is looking for possible costume designed manufacture from Holographix, Northrop Grumman, Polyoptics, Suss MicroOptics.

Northrop Grumman (AOA Xenetics)
Lytro Camera prototype used this manufacturer

http://www.northropgrumman.com/BusinessVentures/AOAXinetics/IntelligentOptics/Products/Pages/MonolithicLensletModules.aspx

Holographix

http://holographix.com/custom-microlens-arrays.html

Newport -- not suitable: focal length too long

https://www.newport.com/f/microlens-arrays

Edmund -- not suitable: focal length too long

https://www.edmundoptics.com/optics/optical-lenses/specialty-lenses/microlens-arrays/3144/

Thorlabs -- not suitable: focal length too long

https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=2861

Polyoptics

http://www.polyoptics.de/site/com/competences/solutions

SUSS MicroOptics

http://www.suss.ch/products-solutions/microlens.html

Plenoptic Image Reconstruction

Reconstruction Algorithm:

The micro lens array (MLA) is placed near the focal point of system. As a result, the exit pupil of the system that was at infinity is imaged onto the sensor plane. From pupil images we can reconstruct both the focused image and the image that is a certain distance defocused. The maximum defocus distance a plenoptic system can reconstructed back to focus is depended on the size of the pupil image. The more pixels that a micro lens has, the more angular information that a system can get. However, because the total amount of pixels is limited, more pixels used for angular information means fewer for spatial resolution. After discussion with our customer, we decided to 5x5 matrix of pixels for each micro lens as a trade-off between the spatial and angular information.

To characterize output the system, we used the Geometric Bitmap Image Analysis function in Zemax to simulated the output from an image put at the object position. Figure 12-1 and figure 12-2 are the input and raw output. The input is a 1024x540 grayscale scenic picture. To simulate a 3D object in the real world, this input is then defocused by 150 μm to get a defocused output.

Figure 12-1: Input Object

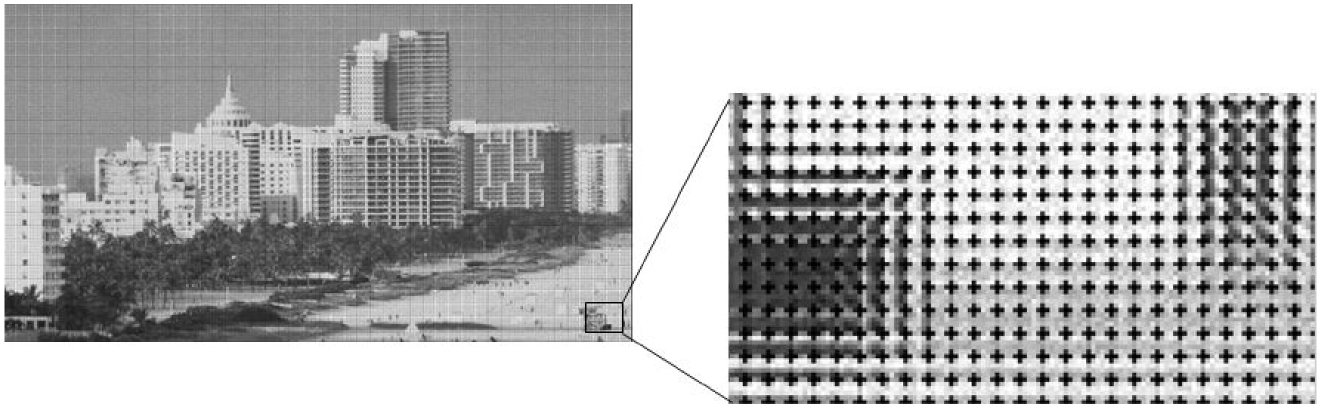

Figure 12-2: Raw Plenoptic Image without Any Reconstruction

As shown in figure 12-2, the raw output is a 4095x2160 image that contains 819x432 pupil images. To construct the image from these pupil images, we need to find the correct pixels value to use to for the pixel in the final image. Ray fan tracings when the system is in focus and out of focus are performed to illustrate this process.

When the object is in focus, as shown in figure 13-1, each group of 5x5 sensor pixels corresponds to one reconstructed pixel. The pattern within the pixel group corresponds to one field point. Since each pixel in the final image is an average of the exit pupil at that field point, the correct pixel value can be calculated by averaging each 5x5 pixel group.

When the object is out of focus, as shown in figure 13-2, the pupil is distributed among adjacent pixel groups by the microlenses. What we need to do then is to pick out the correct pixels from different pixels groups and average them to find the pixel value in the final image.

To better illustrate the reconstruction process, figure 14 shows the distribution of the light from an on-axis point object that is in focus and 150 μm out of focus. On the left is the distribution when this point source is in focus so all the energy is within one pupil image. On the right is the distribution when this point source is 150 μm out of focus. As we can see, the energy from the same point source is distributed among adjacent pixel groups. The reconstruction algorithm gathers all the information from related pixels and average them.

The future work on algorithm for our customer will focus on creating the algorithm that will work for all defocus length between 0 and 150μm. For now the algorithm could only work properly with object defocused at these two end points. Another direction of future study for our customer will be to utilize the Fourier Transform of the pupil to further improve performance of this plenoptic system.

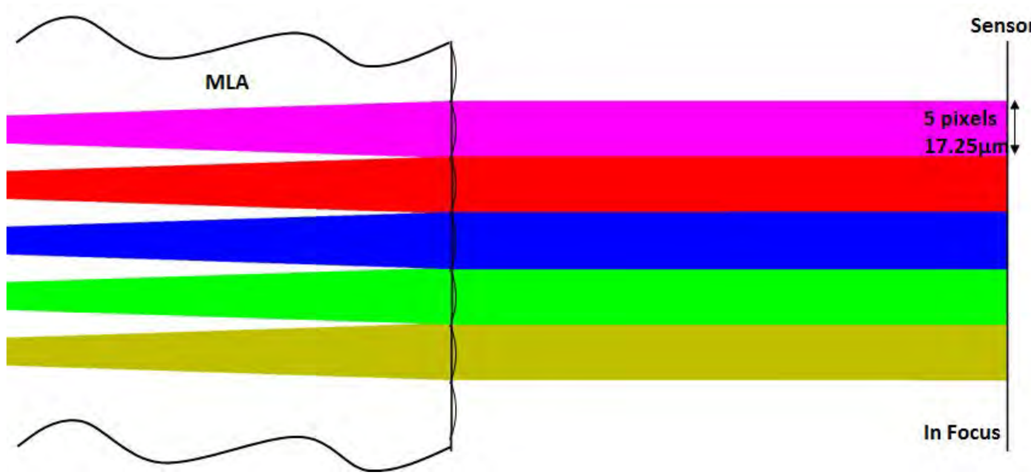

Figure 13-1: Ray fan tracing of five field points in pupil imaging. Top: in focus; Bottom: 150 µm out of focus.

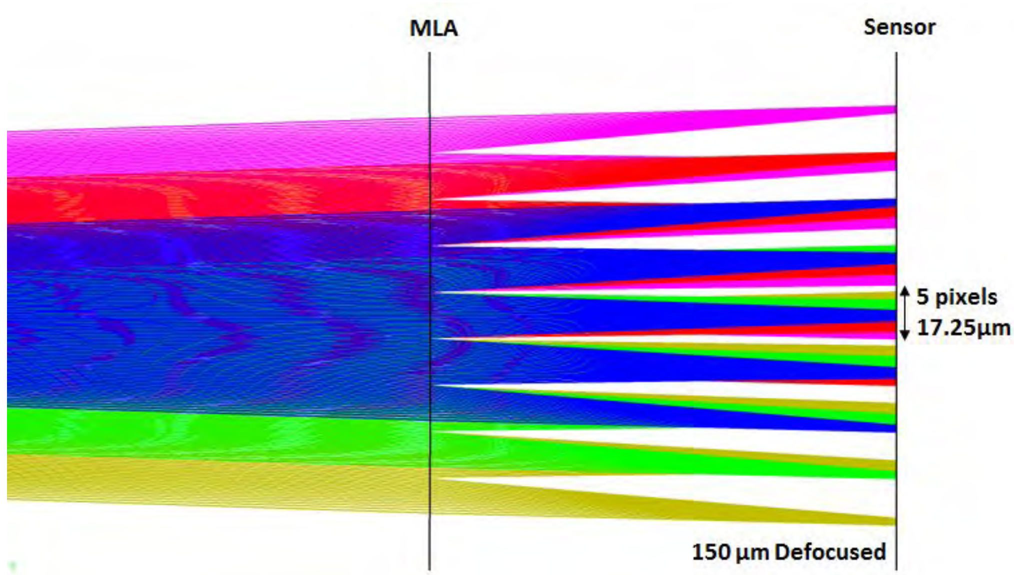

Figure 13-2: Ray fan tracing of five field points in pupil imaging. Top: in focus; Bottom: 150 µm out of focus.

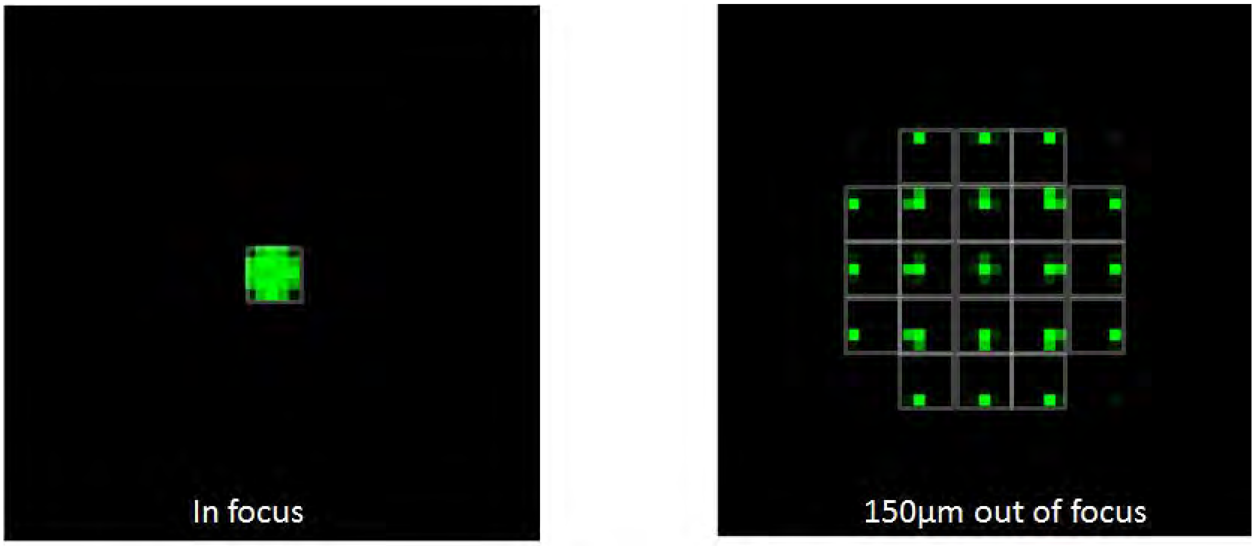

Figure 14: Sensors Plane Illumination from an On-Axis Point Source. Left: object in focus; Right: object with 150 µm defocus. The white boxes are 5x5 pixel groups that correspond to a microlens. The green dots are the distribution of photons from an on-axis point source.

Reconstruction Result:

This section demonstrates the reconstruction results in two defocus scenarios. Figure 15-1 shows the image reconstruction result of an object in focus. The resulting image gives a lower resolution but still clear to eye than the input. However, as shown in figure 15-2, same reconstruction process assuming object in focus does not work properly for an object out of focus, which is essential since real world objects are 3 dimensional with depth. By applying the algorithm in out of focus case, the image constructed, shown in figure 15-3, could have a resolution close to that of the result in focus.

Figure 15-4 provides a comparison of a zoomed area from the same image, from left to right, corresponding to 15-1, 15-2 and 15-3. This detailed area is also the enlarged section in figure 12-2. In figure 15-4, both left (in focus with in focus algorithm) and right (out of focus with out of focus algorithm) could give clear image with relatively high resolution, while the middle image (out of focus with in focus algorithm) has low resolution.

Figure 15-1: Object in focus - image reconstruct.

Figure 15-2: Object out of focus - image reconstruction assuming object in focus.

Figure 15-3: Object out focus - image reconstruction to correct for defocus.

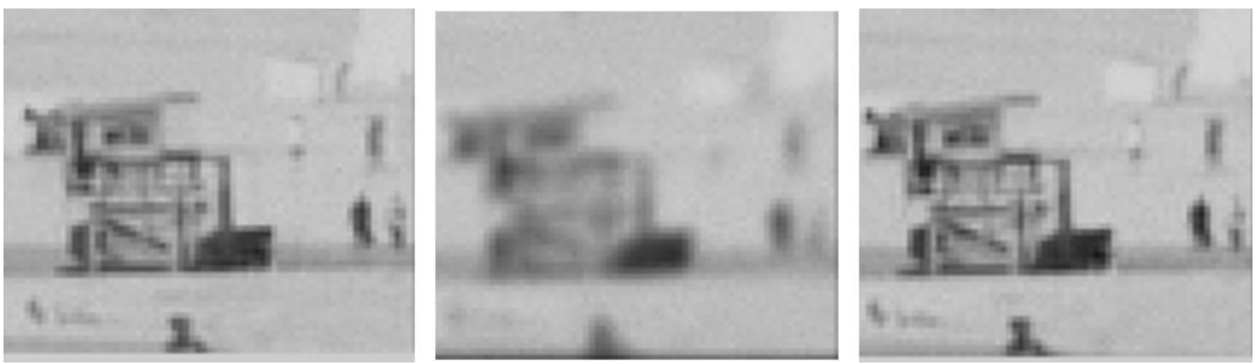

Figure 15-4: The reconstructed images in zoom (part shown in figure 12-2). Left: Object in focus, from 15-1. Middle: Object out of focus, from figure 15-2. Right: Object out of focus with defocus correction, from figure 15-3.

Appendices

Appendix A. Design Details

Table 2. Design Details for Each Surface

Plenoptic Imaging System

	Y Radius	Thickness	Glass
OBJECT:	INFINITY	90.000000	
1:	66.26448	5.000000	STIH4_OHARA
2:	-1052.66246	27.223831	
3:	33.51669	5.000000	SBSL7_OHARA
4:	-63.24833	4.000000	SLAH58_OHARA
5:	29.63695	2.234869	
6:	38.12585	4.375267	SFPL51_OHARA
7:	-107.80247	5.000000	
STOP:	INFINITY	3.000000	
9:	INFINITY	0.000000	
10:	INFINITY	1.000000	SBSL7_OHARA
11:	INFINITY	3.000000	
12:	27.29297	4.500000	SFPL55_OHARA
13:	-57.47776	15.450897	
14:	-29.25648	2.701964	SNBH55_OHARA
15:	30.56564	57.055900	
16:	-195.18495	5.405080	STIH53_OHARA
17:	-76.73987	0.000000	
18:	INFINITY	3.000000	
19:	-2262.73624	4.000000	SNBH51_OHARA
20:	88.00850	6.276336	SFPM2_OHARA
> 21:	-73.77915	170.768666	
IMAGE:	INFINITY	0.000000	

Appendix.B. Revised Timeline

Fall Semester:

December:

~~Finish Product Requirement Document.~~

~~Start preliminary design for objective lens, tube lens and relay stage.~~

Spring Semester:

January:

~~Continue working on preliminary design:~~

- ~~Determine whether the system functions optimally at 1x or 2x.~~
- ~~Work on reducing color aberrations.~~
- ~~Put the entire system together and begin to optimize.~~

February:

~~Optimize the optical system.~~

~~Adjust glasses for better manufacturability.~~

~~Study the micro-lens array.~~

March:

~~Choose the proper micro-lens array.~~

~~Optimize the design of system as a whole with: objective lens, tube lens, relay stage, micro-lens array and sensor.~~

~~Tolerance and possible redesign if necessary.~~

April:

Prepare for final presentation for the class and to the customer.

Note:

If our team can finish the design of the system ahead of schedule, we will send the design to Navitar's rapid prototyping team, who will build the system in 2-5 weeks. During that time, we will work on designing an experiment to conduct with the finished product.

Appendix C. Other design forms

Design Form 2:

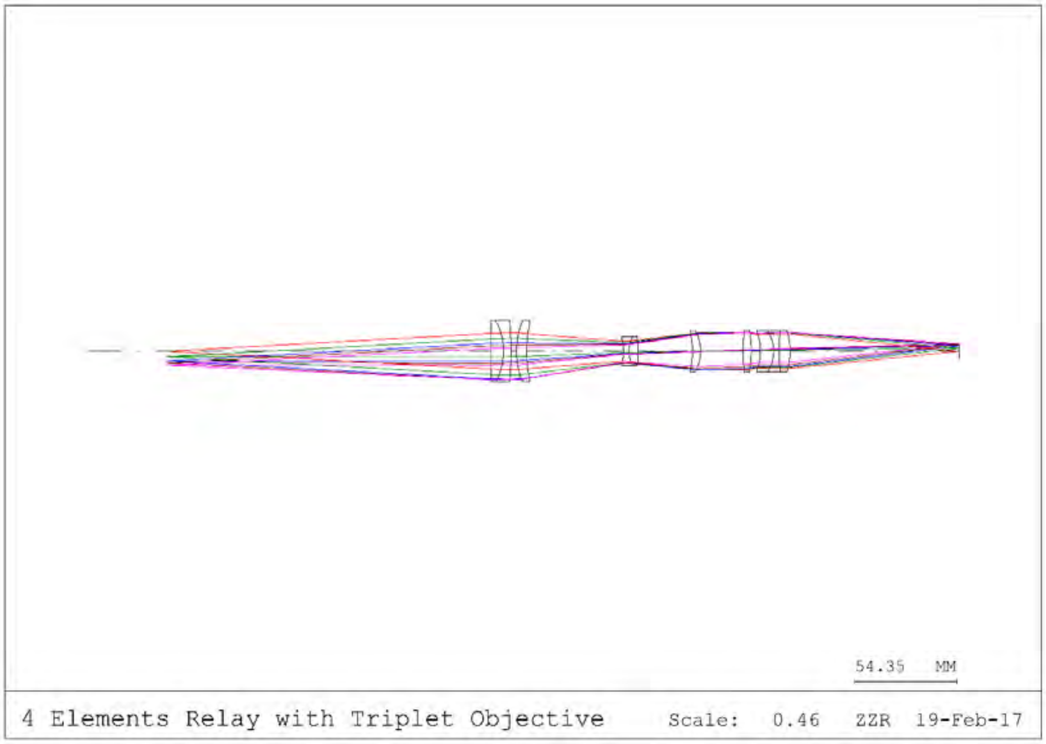

Figure 11. Lens Display of Design

System Data... Surface Properties...

Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Aperture
Object		Sphere	Infinity	172.6165		Refract	
1		Sphere	645.1886	6.7507	SBSM15_OH	Refract	15.0000
2		Sphere	-33.5022	4.0000	LF5HTI_SC	Refract	15.0666
3		Sphere	-187.9140	3.0000		Refract	15.1357
4		Sphere	Infinity	0.0000		Refract	15.0217
5		Sphere	43.5522	5.3841	NSF6HT_SC	Refract	14.9383
6		Sphere	72.3511	51.4781		Refract	14.1988
7		Sphere	-27.5906	3.0000	SF4_SCHOT	Refract	6.4446
8		Sphere	15.7539	4.8928	SFPL51_OH	Refract	6.5504
9		Sphere	-50.8548	28.9049		Refract	6.8720
10		Sphere	-44.8201	4.3401	CAFL_SPEC	Refract	9.5017
11		Sphere	-21.9202	0.0000		Refract	9.8918
12		Sphere	Infinity	5.0000		Refract	9.8233
Stop		Sphere	Infinity	17.6775		Refract	9.6781
14		Sphere	105.9228	4.3687	STIM35_OH	Refract	10.0270
15		Sphere	-56.0324	4.8392		Refract	9.9592
16		Sphere	-27.1088	7.0000	NSF6HTULT	Refract	9.2601
17		Sphere	-19.7575	3.0000	NSF2_SCHO	Refract	9.6995
18		Sphere	127.6173	5.7473	SFPL51_OH	Refract	9.8523
19		Sphere	-38.9045	90.0000		Refract	10.0000
Image		Sphere	Infinity	0.0000		Refract	4.0017

End Of Data

Table 3. Design Details for Design 2.

System Specifications Table:

	Requirement	Design
Magnification	~~1x or~~ 2x	2x
Wavelength	450nm, 550nm, 650nm	450nm, 550nm, 650nm
Working distance	90 mm	90nm
Field of View	8mm diagonal object space	8mm diagonal object space
Total Length	422.5 mm	422 mm
Objective F/#	~~10 (1x)~~ 5 (2x)	5 (2x)
Distortion	<0.25%	<0.25% field curve below
Relative Illumination	>85%	>89.49% across Field relative illumination chart Below
Design MTF	>40% across field ~~at 72.5 lp/mm (1x)~~ or at 145 lp/mm (2x)	>39.2% (147 lp/mm) across field MTF chart below
Telecentricity	Yes, in sensor space	Yes

Table 4. Specification Comparison Table

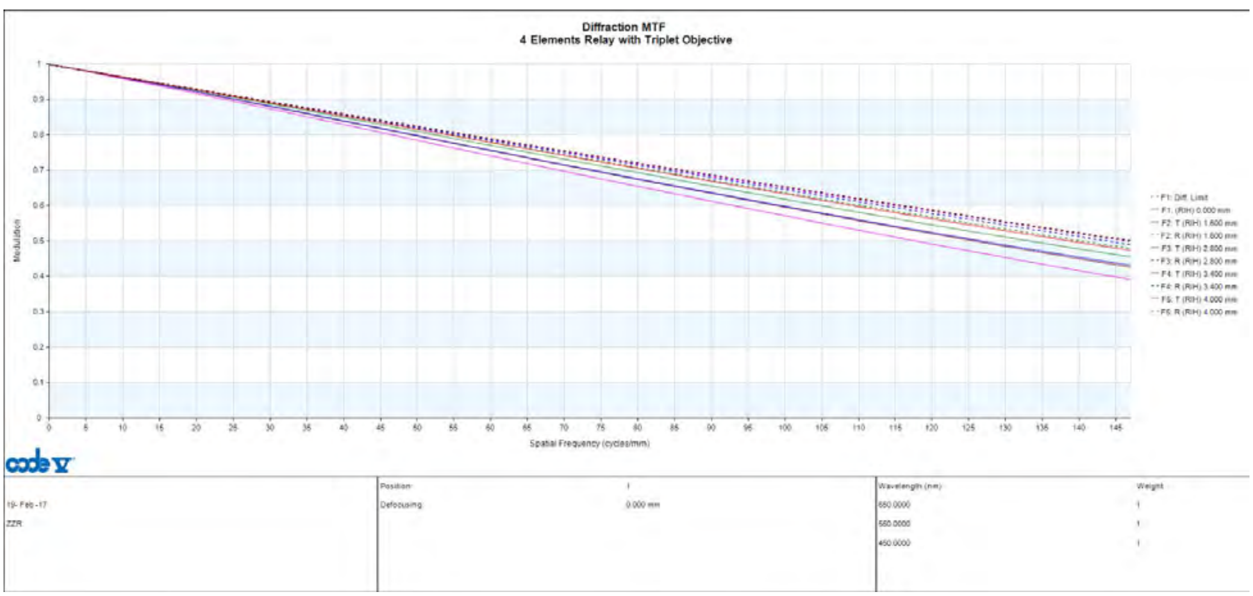

Figure 12. System MTF of Design

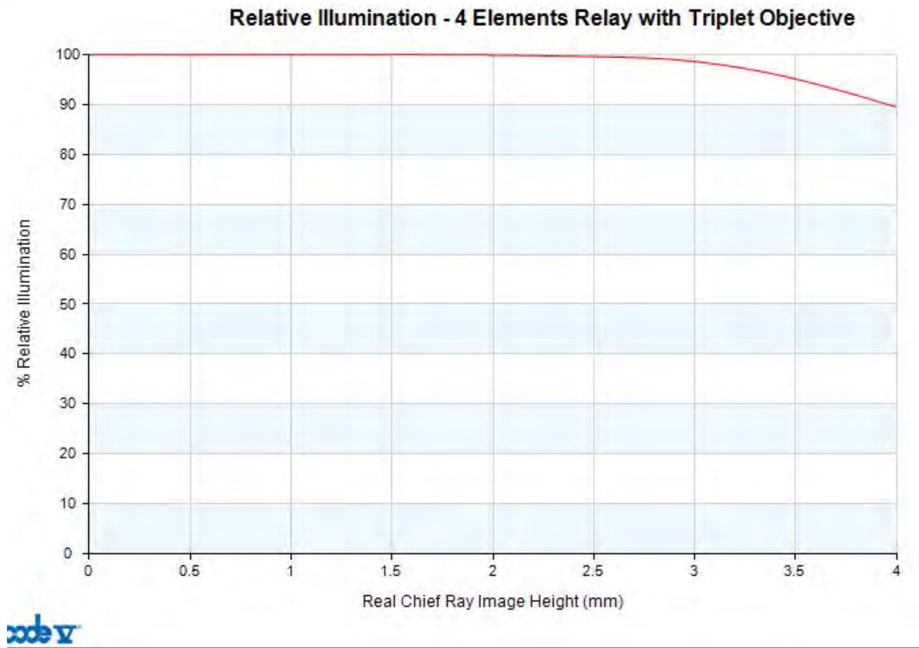

Figure 13. Relative Illumination of Design

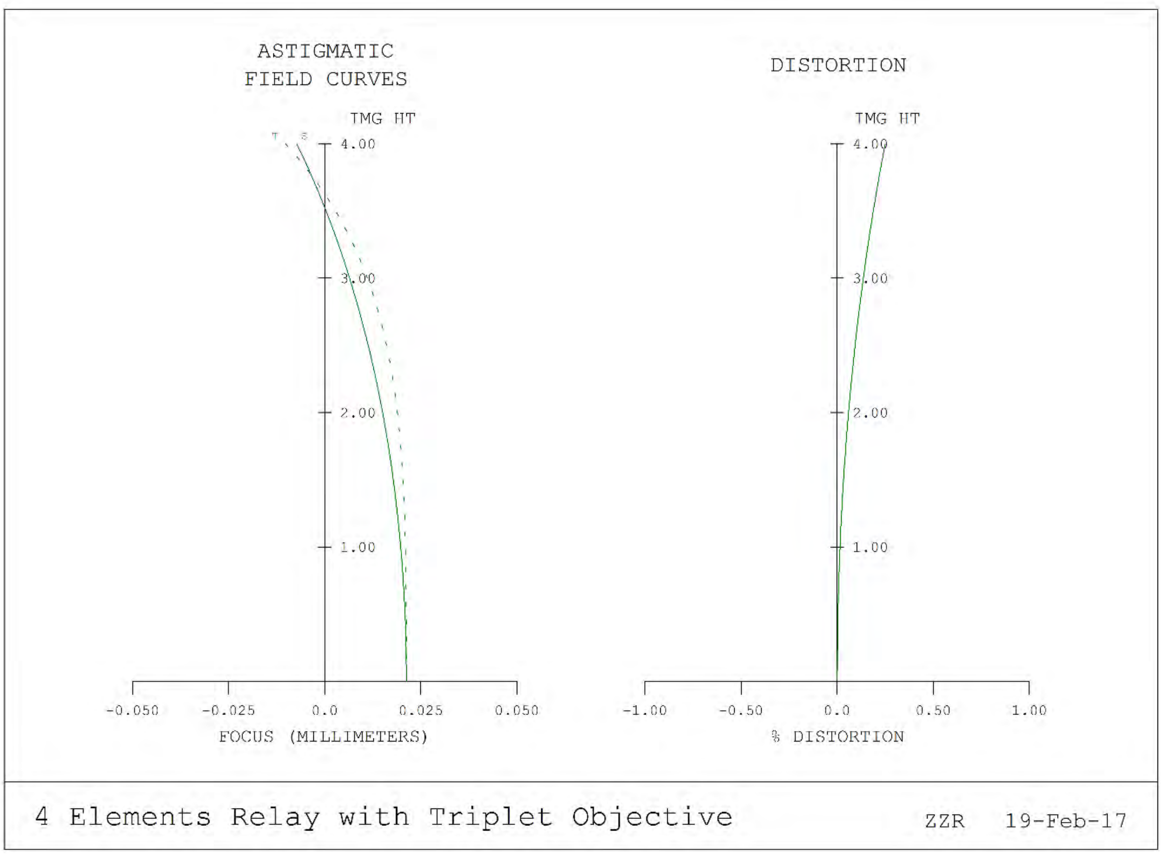

Figure 14. Field Curve of Design

Design Form 3:

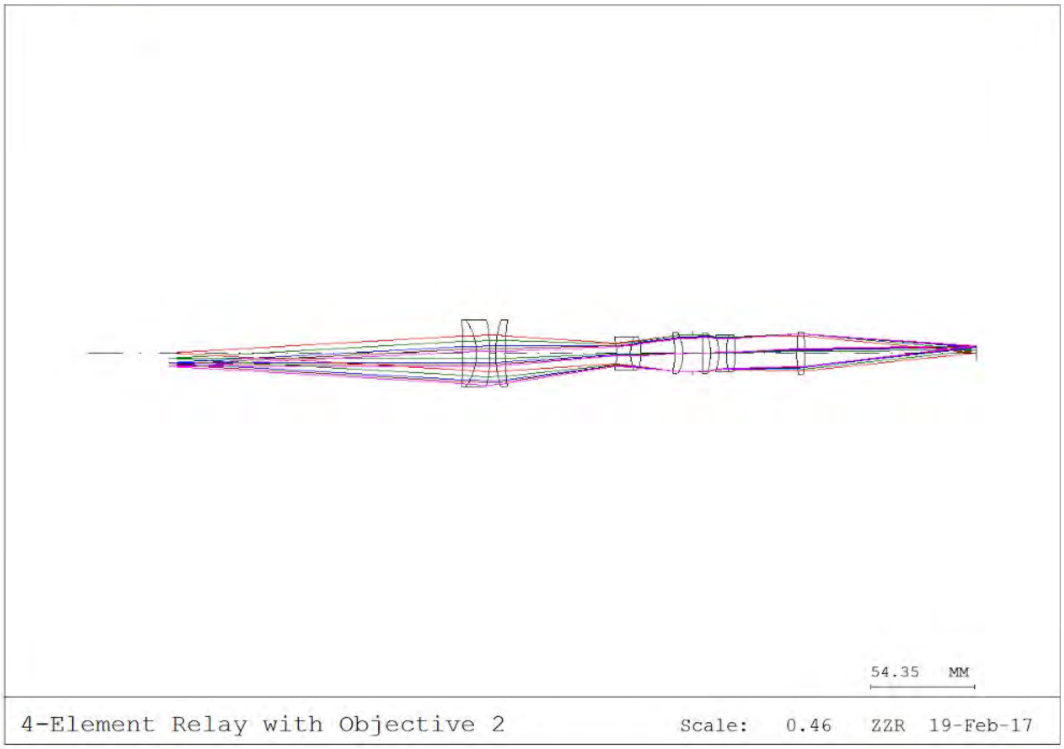

Figure 15. 4 Lens Display of Design

Surface #	Surface Name	Surface Type	Y Radius	Thickness	Glass	Refract Mode	Y Semi-Apertur
Object		Sphere	Infinity	153.6244 V		Refract	
1		Sphere	-216.8167 V	7.0000 V	NSK2HT_SC	Refract	16.0000
2		Sphere	-30.0494 V	7.0000 V	SBAL2_OHA	Refract	15.9333
3		Sphere	-85.2871 V	3.0000 V		Refract	16.4400
4		Sphere	Infinity	0.0000		Refract	16.2904
5		Sphere	57.0156 V	5.0000 V	PSF69_SCH	Refract	16.2139
6		Sphere	133.7558 V	58.4272 V		Refract	15.7057
7		Sphere	-20.6130 V	7.0000 V	SF4_SCHOT	Refract	6.6881
8		Sphere	20.5680 V	5.5764 V	SFPL53_OH	Refract	7.2589
9		Sphere	-24.6122 V	17.6997 V		Refract	7.7520
10		Sphere	-40.8003 V	4.2966 V	FK5HTI_SC	Refract	9.4092
11		Sphere	-21.3534 V	0.0000		Refract	9.8282
12		Sphere	Infinity	5.0000		Refract	9.7309
Stop		Sphere	Infinity	5.0000 V		Refract	9.5280
14		Sphere	28567.4473 V	4.2795 V	NSF6HTULT	Refract	9.5542
15		Sphere	-36.5607 V	4.2550 V		Refract	9.5803
16		Sphere	-31.5694 V	4.0000 V	PSF8_SCHO	Refract	8.6480
17		Sphere	32.8590 V	4.2252 V	FK5HTI_SC	Refract	8.6225
18		Sphere	-518.2834 V	32.6158 V		Refract	8.7214
19		Sphere	78.5033 V	4.0000 V	NSF5_SCHO	Refract	10.0843
20		Sphere	-149.2839 V	90.0000		Refract	10.0000
Image		Sphere	Infinity	0.0000		Refract	4.0017

Table 5. Design Detail of Design

System Specifications Table:

	Requirement	Design
Magnification	~~1x or~~ 2x	2x
Wavelength	450nm, 550nm, 650nm	450nm, 550nm, 650nm
Working distance	90 mm	90nm
Field of View	8mm diagonal object space	8mm diagonal object space
Total Length	422.5 mm	422 mm
Objective F/#	~~10 (1x)~~ 5 (2x)	5 (2x)
Distortion	<0.25%	<0.25% field curve below
Relative Illumination	>85%	>91.26% across Field relative illumination (see chart below)
Design MTF	>40% across field ~~at 72.5 lp/mm (1x)~~ or at 145 lp/mm (2x)	>37.7% (147 lp/mm) across field MTF chart below

Table 6. Specification Comparison Table for Design Three

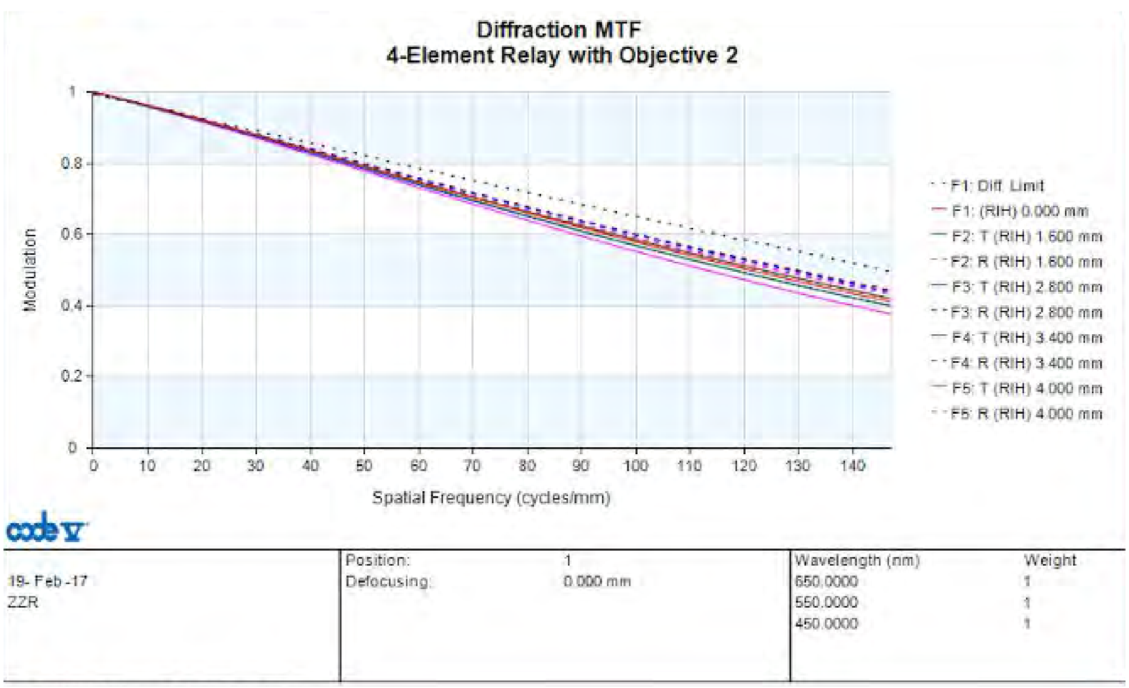

Figure 16. System MTF of Design

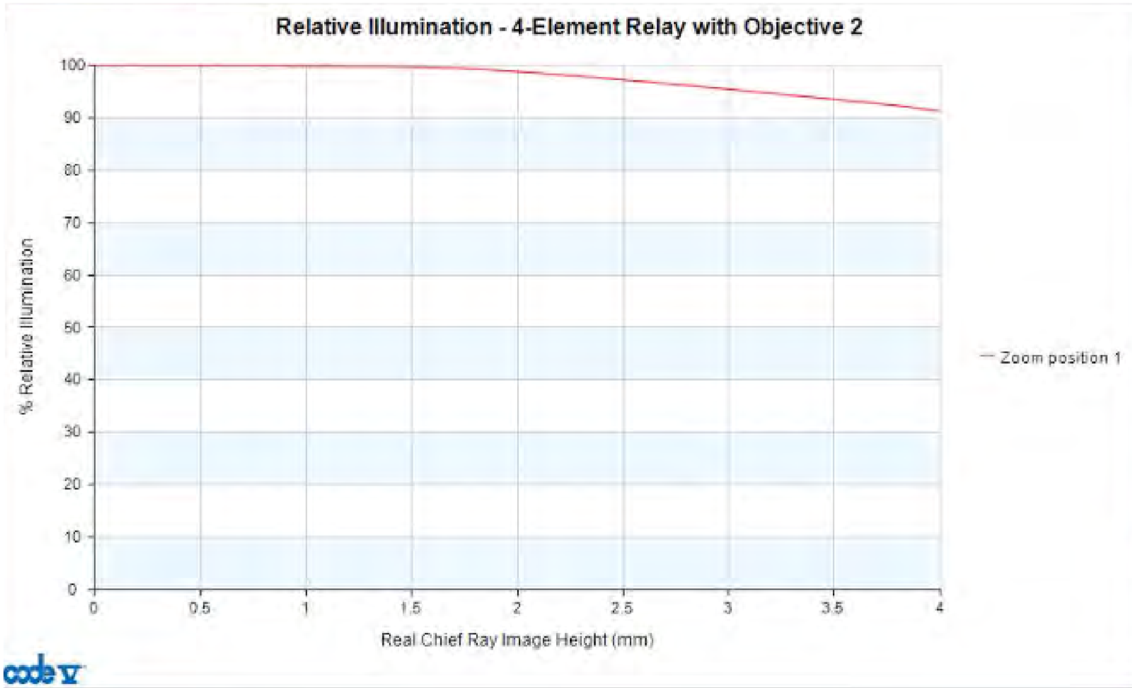

Figure 17. Relative Illumination of Design

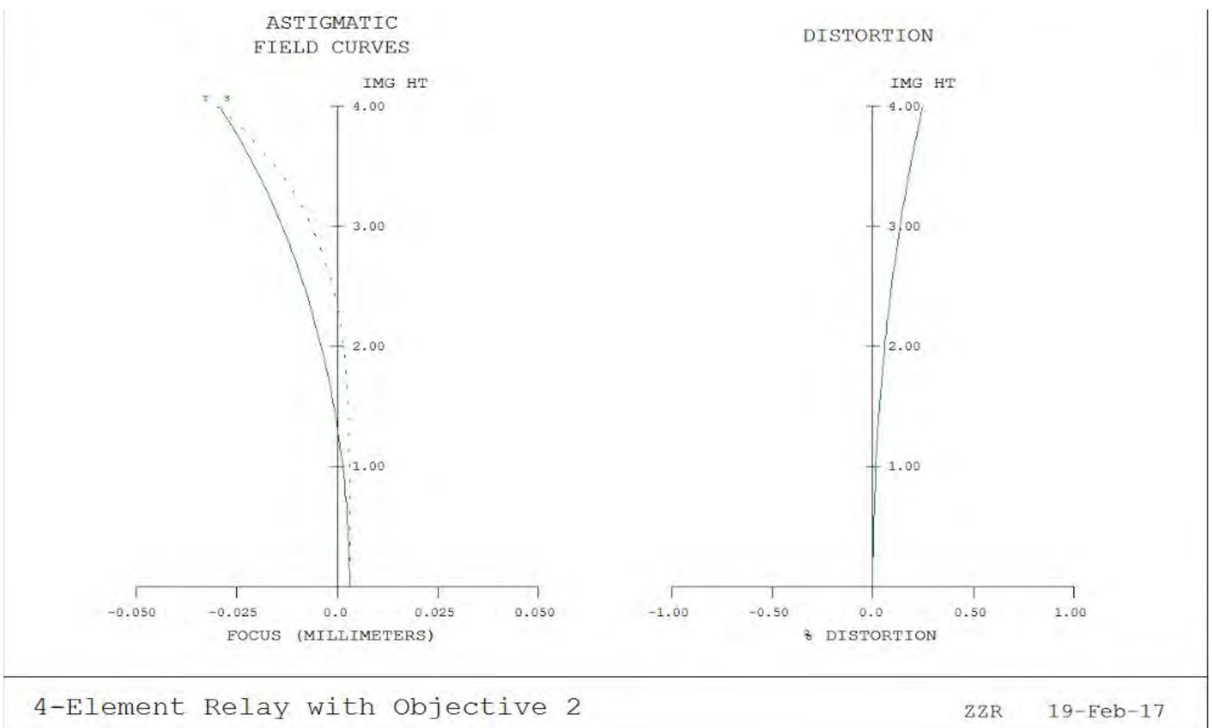

Figure 18. Field Curves of Design

Appendix D. Tolerancing Specifics

Singlet Elements Tolerance

Test Plate Fit Tolerance (DLF)	5.0
Irregularity Tolerances (IRR)	0.25
Thickness Tolerance (DLT)	0.025
Refractive Index Tolerances(DLN)	0.0002
V-number Delta(DLV)	0.002
Element Wedge Tolerances (TIR)	Semi-DIameter into arcminute
Barrel Tilt Tolerances (BTI)	0.00035
Group Displacement Tolerances (DIS)	0.0175

Doublet Without Cement Tolerance

Test Plate Fit Tolerance (DLF)	2.0
Irregularity Tolerances (IRR)	0.25
Thickness Tolerance (DLT)	0.025
Refractive Index Tolerances(DLN)	0.0002
V-number Delta(DLV)	0.002
Element Wedge Tolerances (TIR)	Semi-DIameter into arcminute
Barrel Tilt Tolerances (BTI)	0.00030
Group Displacement Tolerances (DIS)	0.0175
Roll Tolerances (ROL)	0.0050

Filter Tolerances

Test Plate Fit Tolerance (DLF)	5.0

Irregularity Tolerances (IRR)	0.25
Thickness Tolerance (DLT)	0.025
Refractive Index Tolerances(DLN)	0.0002
V-number Delta(DLV)	0.002
Element Wedge Tolerances (TIR)	Semi-DIameter into arcminute
Barrel Tilt Tolerances (BTI)	0.00035
Group Displacement Tolerances (DIS)	0.0175

Compensators

Thickness Tolerance (DLT)	Object Position 1.0
Group Displacement Tolerances(DIS)	(Surface 3 to 5) 0.1