LENS DESIGN USING HYBRID CODED NSGA2

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OUTLINE

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- TRIPLET DESIGN PROBLEM.
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- WHY MULTI-OBJECTIVE GA?
- WHAT IS HYBRID CODING?
- WHY HYBRID CODING?
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LENS DESIGN FUNDAMENTALS

- Optical System Optimization
  - Aberrations
  - Definition of Objective Functions or Merit Functions.
  - Definition of Constructional Parameters.
  - Linear Algebra based formulation of Merit Function.
- Ray Tracing
- Traditional Single Objective Optimization Procedure
- Proposed Multi-Objective Optimization Procedure.

ABERRATIONS

- Aberrations are the representations of deviations from linear correspondence between an object and its image.
- In ray optics, we have aberrations in our system, if a unique point in object space does not map to a unique point in image space linearly. In wave optics, if we have a spherical incident wave front and a non spherical out going wave front for an optical system, we have aberrations present.
- Aberrations are classified in such a way that we can visually identify them while still making them orthogonal to each other. It is the shape of the ray fan plots and spot diagrams that help us identify the aberrations.
- A ray fan plot is the value of Transverse Ray Aberration (TRA) plotted as a function of normalized radial distance on pupil.
- TRA is the distance between the ideal image point and the actual image point on the chosen image plane in the transverse direction.
- We obtain ray fan plots by letting the rays from an off axis point incident along a single line in the pupil.
- Spot diagrams are obtained by uniformly illuminating a pupil in two dimensions by rays originating from a single object point. The distribution of ray pierces on the image plane can help us identify various aberrations.

ABERRATIONS (continued)

- The wave front aberrations are considered when the aberration effects in the system are closer to the diffraction limited performance.
- For each point in the exit pupil (x, y), we describe the optical path difference W (x, y) between the aberrated wave front and the spherical reference surface. We can describe W either using Seidel polynomials as done in Optical design or using Zernike polynomials as done during the optical testing. Using Seidel polynomials [see Geary] we can write,

$$W = \sum_{i,j,k} W_{ijk} \bar{H}^{i} \rho^{j} \cos^{k} \phi$$

- Here, the four terms in the expansion above are the wave front aberration coefficient, fractional image height; normalized pupil radius ($\rho = \frac{y}{r}$) and the cosine of the other pupil coordinate in the given order.
- The distance between the exit pupil and the paraxial plane is R. The Transverse ray aberration can be calculated from W by using

$$T = -(\frac{R}{r})\frac{dW}{d\rho}$$

MERIT FUNCTION
&
CONSTRUCTIONAL PARAMETERS

- An optical system will have a number of constructional parameters which specify the system. These include the radius of curvatures of the lens elements, the distance between various surfaces, position of stops etc. Let the system be having M aberrations defined over a space of N constructional parameters. The symbols and definitions used are those used by Vasiljevic.
- The merit function is defined by

$$\Phi = \sum_{i=1}^{M} f_i^2(x_1, x_2, \ldots\ldots x_N)$$

- Where f are the aberrations and X is a vector of constructional parameters and

$$X = (x_1, x_2, \ldots\ldots x_N)$$

refers to a point in the parameter space. There can be a number of equality and inequality constraints imposed among the constructional parameters.

LINEAR ALGEBRA BASED FORMULATION OF MERIT FUNCTION

$$X = -(A^T . A)^{-1} . A^T . F_0$$

- where F denote the vector containing the aberration functions which are functions of the constructional parameters. The matrix A with elements a_{ij} is defined as the first partial derivative of f_i with respect to x_i
- The above formulation is for a single objective optimization.
- **The difference when we have multiple objectives is to have different F vectors for different objectives. But the relevant "aberrations" to include might have to be rewritten according to the metric defined for each objective. Hence the A vector and F vectors will be different with different dimensions corresponding to the nature of the objective.**

RAY TRACING

- Snell's Law is the fundamental equation for Ray Tracing.
- Optical Design Software CODE V® was employed to do the ray tracing. Ray tracing and evaluation gives us values for the required objective functions.
- CODE V® interacts with NSGA2 written in C through the COM interface of Visual Studio. (This interface is very slow.)

TRADITIONAL SINGLE OBJECTIVE OPTIMIZATION PROCEDURE

- First order lay out based on paraxial (Gaussian) approximation.
- Based on Optical Engineering insight, form a Merit Function (Objective Function) for the required performance criteria. Here the experience of the designer DOES MATTER.
- Optimize the Merit function. Try different local optimization techniques.
- Try different starting points.
- Try various global optimization techniques.
- Analyze the results for manufacturability. Conduct a Tolerance Analysis.

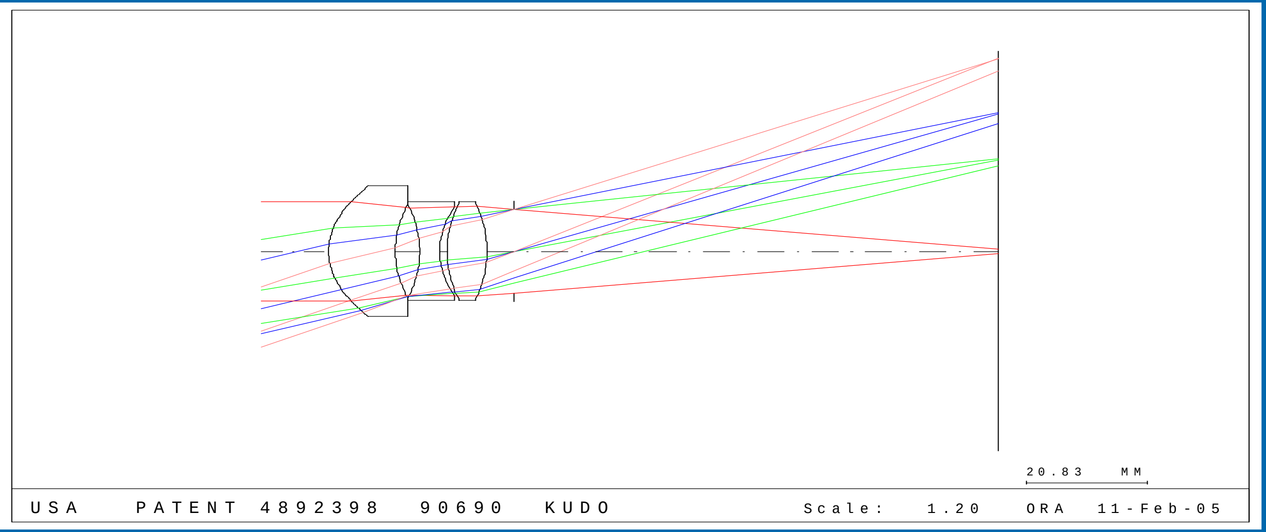
PROPOSED MULTI-OBJECTIVE OPTIMIZATION PROCEDURE

- Choose Multiple Merit functions consistent with the performance requirement.
- Optimize using Multi-Objective Evolutionary Algorithms.
- Use these solutions as a starting point and conduct Single Objective local and global Optimization for suitably chosen Merit function.
- Analyze for manufacturability. Conduct Tolerance Analysis.
- The following Improvements are anticipated.
  - Reduced dependence on Optical Engineering insight in choosing suitable starting points and Merit function.
  - Obtain multiple and Diverse Pareto-Optimal Solutions in a single run.
  - Obtain multiple manufacturing choices for a given performance.

TRIPLET DESIGN PROBLEM

- Minimize Seidel Aberration Coefficients corresponding to Spherical Aberration (SA) and Distortion (DST).
- Obtain Diverse Pareto-Optimal Solutions.
- Use them as a set of Diverse starting points for Single Objective Local and Global Optimizations. (Selection of proper starting point is usually difficult). Here the Default Merit Function from CODE V® is used.

ORIGINAL DESIGN



This is the ORIGINAL DESIGN chosen from Patent Literature. We would like to improve up on our two objectives, minimization of coefficients of Spherical Aberration (SA) and Distortion (DST). There are 13 variables. They are 6 radii, 3 glass thickness, 2 air gaps, 1 distance from the last glass surface to the stop, distance between the paraxial image and real image.

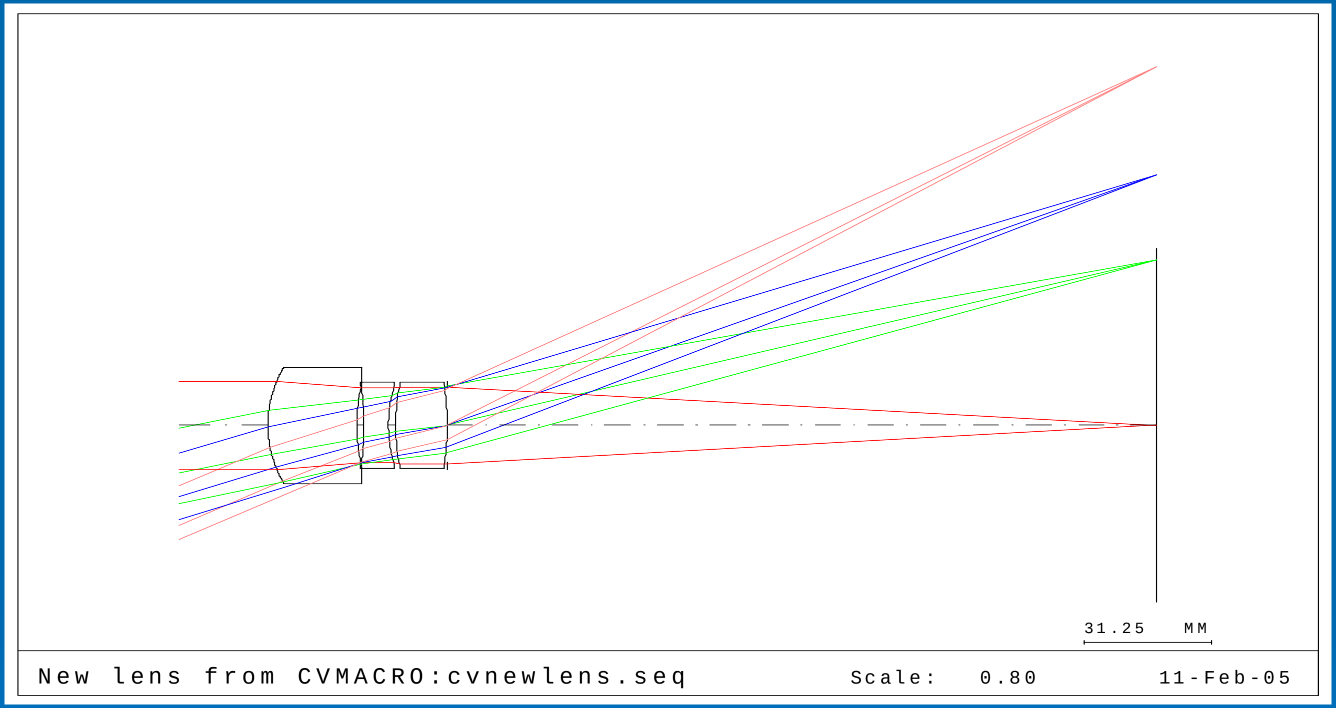
ABERRATION COEFFICIENTS AND FIRST ORDER QUANTITIES FOR THE ORIGINAL

- THO SO..I
- USA PATENT 4892398 90690 KUDO
- Position 1, Wavelength = 587.6 NM

	SA	TCO	TAS	SAS	PTB	DST	AX	LAT	PTZ
1	-1.390593	0.360706	-2.783492	-2.762700	-2.752304	0.238872	-0.447814	0.038720	-0.011528
	0.033922	-0.126032	0.156085	0.052028		-0.064435	ASPHERIC CONTRIBUTIONS		
2	0.008142	0.067503	2.003355	1.878991	1.816810	5.192648	0.141447	0.390892	0.007610
3	0.679764	-5.201052	15.155950	6.312706	1.891084	-16.100049	0.585990	-1.494520	0.007921
4	3.839458	6.651639	6.469198	3.908403	2.628005	2.257027	1.005447	0.580626	0.011008
5	-2.647614	-6.825646	-7.995123	-4.084731	-2.129535	-3.510195	-0.763196	-0.655849	-0.008920
6	-1.083630	6.278366	-14.212379	-6.128876	-2.087125	11.836548	-0.601072	1.160835	-0.008742
STO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SUM	-0.560551	1.205484	-1.206406	-0.824178	-0.633065	-0.149584	-0.079199	0.020704	-0.002652

- INFINITE CONJUGATES
- EFL 100.0045
- BFL 83.5412
- FFL -88.9858
- FNO 3.4908
- IMG DIS 82.7638
- OAL 31.8530
- PARAXIAL IMAGE
- HT 57.7376
- ANG 30.0000
- ENTRANCE PUPIL
- DIA 28.6483
- THI 30.7264
- EXIT PUPIL
- DIA 23.9321
- THI 0.0000

ORIGINAL OPTIMIZED USING CODE V® LOCAL OPTIMIZER

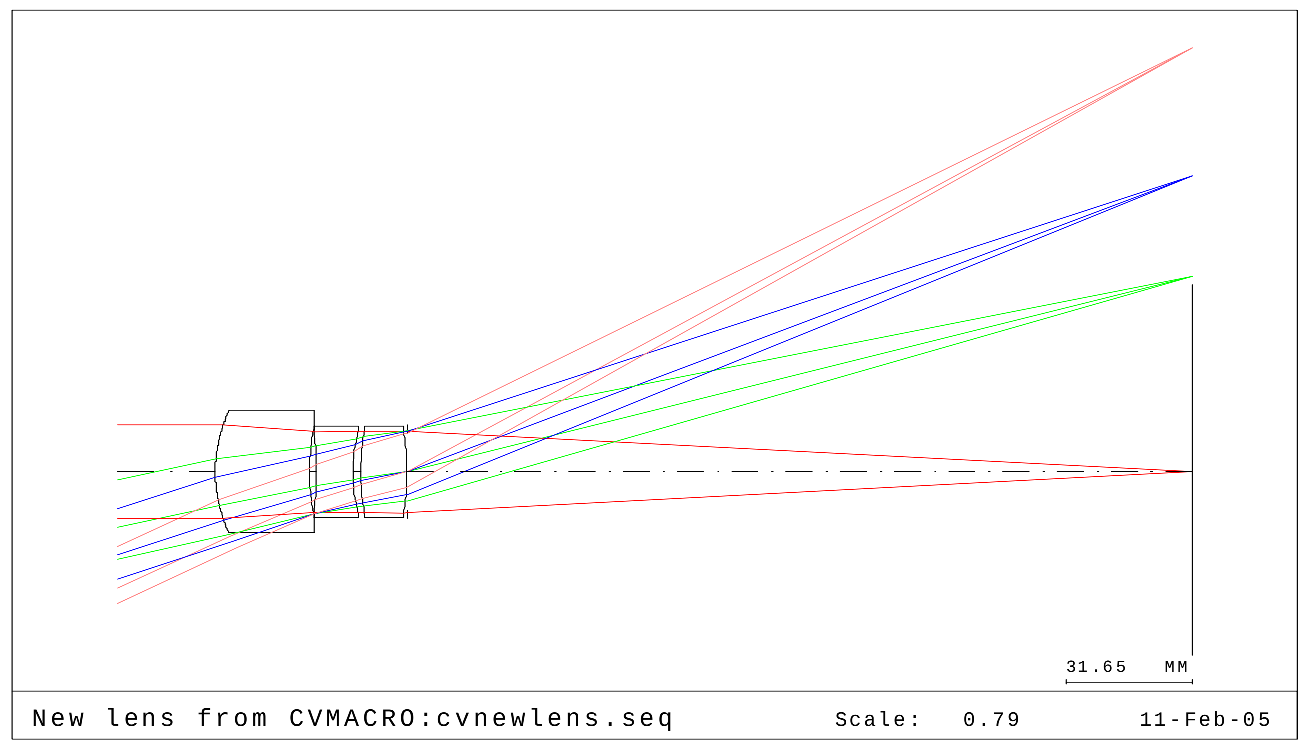


ABERRATION COEFFICIENTS AND FIRST ORDER QUANTITIES FOR THE LENS OBTAINED FROM ORIGINAL USING CODE V® LOCAL OPTIMIZER

- THO SO..I
- New lens from CVMACRO:cvnewlens.seq
- Position 1, Wavelength = 587.6 NM
- SA TCO TAS SAS PTB DST AX LAT PTZ
- 1 -0.608133 -0.812664 -3.698325 -3.456995 -3.336330 -1.539892 -0.542838 -0.241803 -0.006865
- 0.000000 0.000000 0.000000 0.000000 0.000000 ASPHERIC CONTRIBUTIONS
- 2 0.003172 0.051884 2.523470 2.334864 2.240560 12.731372 0.166788 0.909451 0.004610
- 3 0.164913 -2.285896 12.191342 5.150146 1.629548 -23.795822 0.571154 -2.638969 0.003353
- 4 1.314307 5.892809 12.015742 6.144425 3.208767 9.183023 1.138440 1.701432 0.006602
- 5 -0.819748 -5.080800 -13.044253 -6.046292 -2.547312 -12.491650 -0.829371 -1.713483 -0.005241
- 6 -0.199606 2.293413 -10.569996 -4.714309 -1.786465 18.055307 -0.530439 2.031526 -0.003676
- STO 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000
- SUM -0.145095 0.058747 -0.582019 -0.588160 -0.591231

- INFINITE CONJUGATES
- EFL 201.8271
- BFL 174.4329
- FFL -196.6731
- FNO 6.9844
- IMG DIS 173.1540
- OAL 43.8958
- PARAXIAL IMAGE
- HT 116.5249
- ANG 30.0000
- ENTRANCE PUPIL
- DIA 28.8968
- THI 36.8502
- EXIT PUPIL
- DIA 24.9746
- THI 0.0000

LENS OBTAINED FROM ORIGINAL USING CODE V® GLOBAL SYNTHESIS



ABERRATION COEFFICIENTS AND FIRST ORDER QUANTITIES FOR THE LENS OBTAINED FROM ORIGINAL USING CODE V® GLOBAL SYNTHESIS

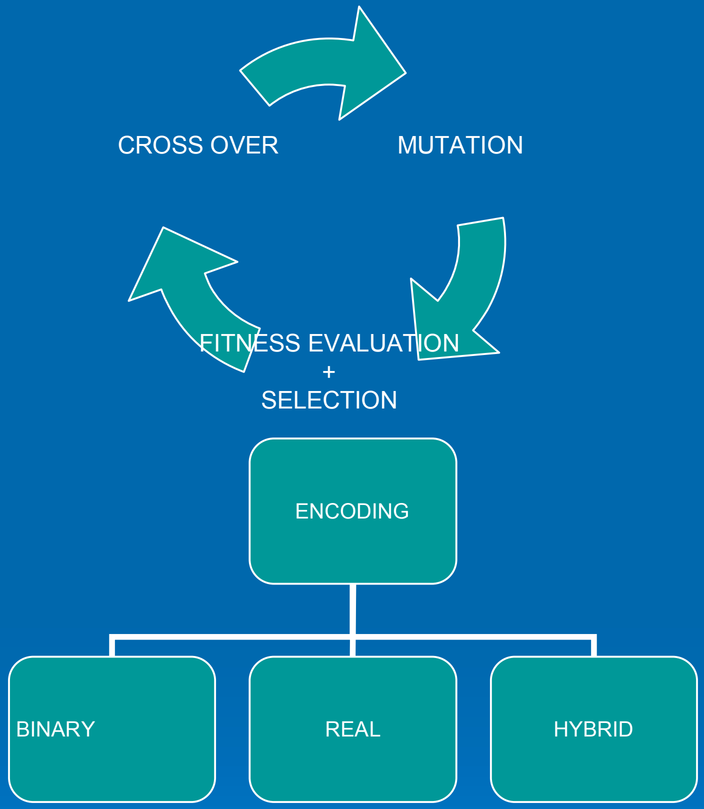
- THO SO..I
- New lens from CVMACRO:cvnewlens.seq
- Position 1, Wavelength = 587.6 NM
- SA TCO TAS SAS PTB DST AX LAT PTZ
- 1 -0.482042 -0.803029 -3.783457 -3.486177 -3.337537 -1.935865 -0.543035 -0.301546 -0.006111
- 0.000000 0.000000 0.000000 0.000000 0.000000 ASPHERIC CONTRIBUTIONS
- 2 0.004330 0.075158 2.708839 2.418970 2.274036 13.994217 0.176006 1.018229 0.004163
- 3 0.132593 -2.037016 12.091551 5.137188 1.660007 -26.307504 0.579293 -2.966554 0.003039
- 4 1.092444 5.659573 12.958098 6.442479 3.184669 11.125417 1.161571 2.005899 0.005831
- 5 -0.707649 -4.917058 -13.973973 -6.381554 -2.585344 -14.780617 -0.858430 -1.988250 -0.004733
- 6 -0.161585 2.058142 -10.527054 -4.701518 -1.788750 19.961351 -0.537644 2.282689 -0.003275
- STO 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000

- SUM -0.121909 0.035770 -0.525996 -0.570612 -0.592919 2

- INFINITE CONJUGATES
- EFL 226.8151
- BFL 197.6181
- FFL -220.3017
- FNO 7.8491
- IMG DIS 196.3041
- OAL 47.9339
- PARAXIAL IMAGE
- HT 130.9517
- ANG 30.0000
- ENTRANCE PUPIL
- DIA 28.8968
- THI 40.0240
- EXIT PUPIL
- DIA 25.1770
- THI 0.0000

WHY GA?

- To obtain Global Optima.



WHY MULTI-OBJECTIVE GA?

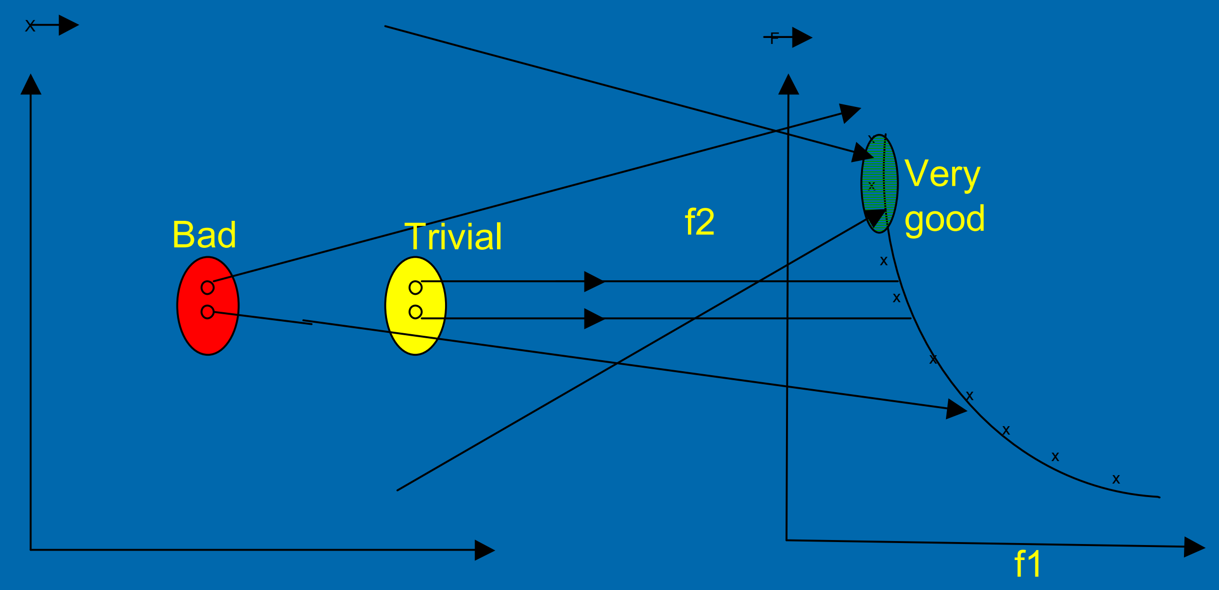
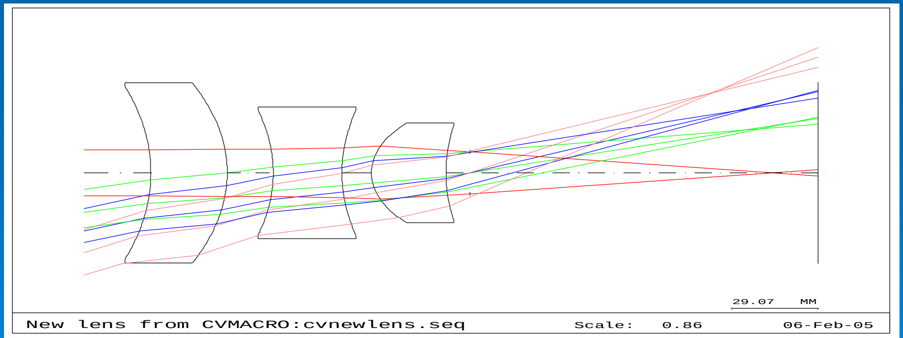


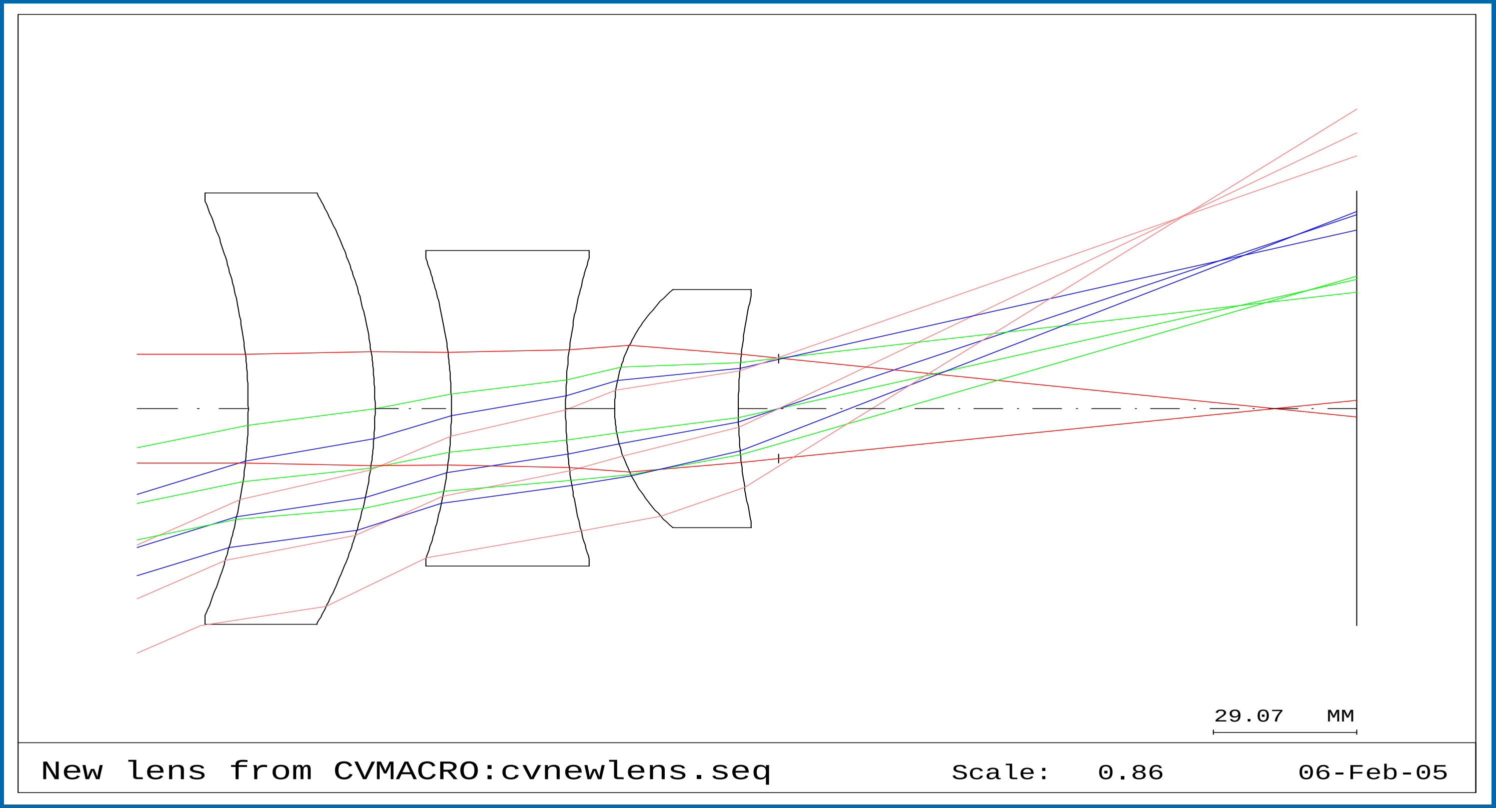
Figure 1. Mapping from Constructional Parameter Space X to the Objective Function Space F is shown. This figure shows three categories of solutions mapped from X to F on a particular Pareto-optimal front. When two nearby points in X maps to two far away points in F, we have an undesired situation. Slight perturbations of parameters during manufacturing can lead to severe performance degrading. When two nearby points in X maps to two nearby points in F, we have the trivial situation. When two far away points in X maps to two nearby points in F, we obtain alternate choices for manufacturing the system.

1. Alternate manufacturing choices for a given performance requirement is possible (see above).
2. Multiple Pareto-Optima can be obtained in a single run.
3. Dependence on Optical Engineering insight can be reduced on selecting suitable merit function and starting points.

WHAT IS HYBRID CODING?

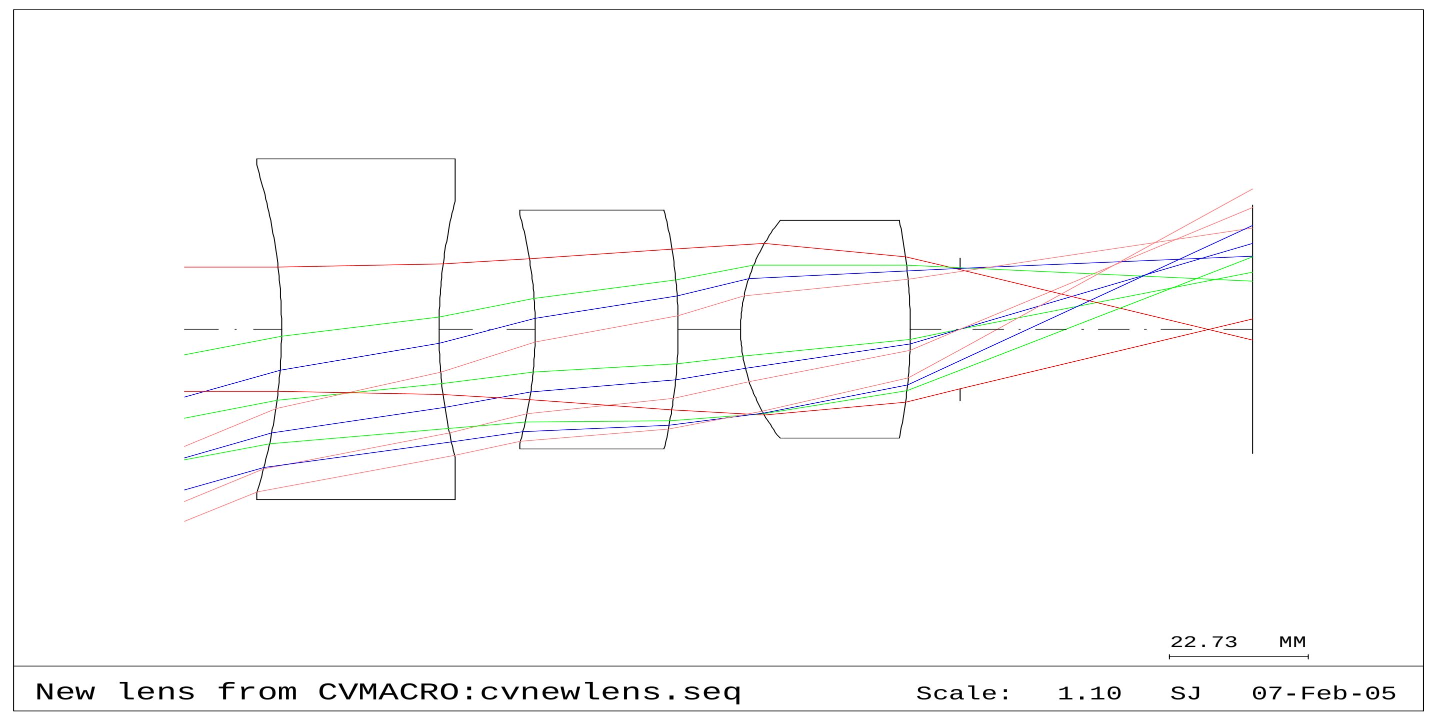
1. Object is placed on the left side of the system.
2. Radius is Positive if Ray Travels from the Vertex of Lens to the Center of Curvature. Otherwise, Radius of curvature is Negative .
3. Define an integer representing the shape of the lens system.
   Assign a Digit (-1) for Positive Curvature and Digit (+1) for Negative Curvature). See the figure below for illustration.
   56 ==111000(binary)==(-,-,-,+,+,+)
4. The value of a radius will come from two different variables. One is a Decimal Number representing the magnitude of radius. The other is the SIGN(+ or -) of the radius. The SIGNS for all the radii are encoded into a single Binary Integer.





This corresponds to the solution 2 in Table 1, belongs to region 56, has F/# 4.4, SA=-1.98 and DST= -0.44. The image is too curved.

56 ==111000(binary)==(-,-,-,+,+,+)



This corresponds to the solution 12 in Table 1, belongs to region 45, has F/# 1.73, SA=-1.9 and DST= -0.49. The image suffers from astigmatism and coma, but image is flat.

45 == 101101 (binary) == (-,+,-,-,+,-)

WHY HYBRID CODING?

REAL CODING OF THE RADIUS IS BAD because…………

- **Abrupt change from positive to negative *INFINITY* at a *FLAT SURFACE*.**
- Very small values of radii are not realizable. They correspond to infinite curvature.
- Difficult to get good solutions when ***any of the six radii of curvatures*** **is less than 10 mm in absolute value.**
- In the beginning, when candidates are randomly generated with radius between **-200 mm and 200 mm, the probability that it lies between -10 mm and 10 mm is 0.05** ***for any one radius.*** Probability that ***any one of the six radii lie between -10 mm and 10 mm is approximately 0.3.***
- *So among the initial generation, 30% of the population members are bound to be bad candidates. Only the remaining 70% are the possible good candidates.*
- In any given generation after the evolution of a Pareto-front, the cross-over takes place between selected candidates. The probability that *a* ***selected pair has at least one radius with opposite signs*** is approximately

{1-(0.5)(0.5)(0.5)(0.5)(0.5)(0.5)} = 0.984.

WHY HYBRID CODING? (continued)

- ***The probability for their magnitudes to differ by at least 20 mm is 0.79.The cross-over is likely to result in children with radii in the prohibited region between -10 mm and 10 mm if the magnitudes of the radii differ by less than 20 mm. This is given by 1-0.79 = 0.21.***

$$(R1 – R2)/2 < 10 \text{ mm}$$

- ***Hence the probability for a selected pair on Pareto-Optimal front generating undesired children after cross over is given by { (0.984)X (0.21)} . This essentially reduces the effectiveness of cross over by a factor of 20%.***

- During cross over, to reach from positive values of radius to negative values of radius, we have to cross positive infinity and negative infinity. Only a hyper cube around the origin of the system (where positive and negative infinities are placed side by side) is the allowed region for the radii.

GA and PROBLEM SPECIFICATIONS

- NSGA2
- Number of generations is 34, Population size is 130
- Cross over probability is 1, real coded mutation probability is 0.0769, Uniform Binary Cross over is employed, binary coded mutation probability is 0.166667 and the cross over parameter in SBX operator is 100.
- The NSGA2 code downloaded from Deb's web site was used with necessary modifications for hybrid coding.
- The radii of curvature is allowed to vary between -200mm and 200mm. The thicknesses were varied from 0.01mm to 30mm.

RESULTS

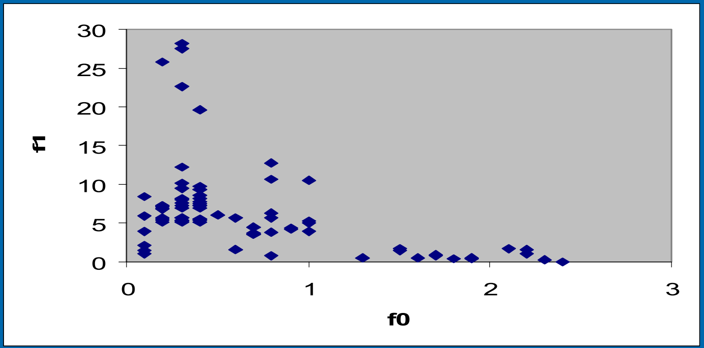


Figure2. A diverse set of good solutions belonging to different Pareto-Fronts is shown.

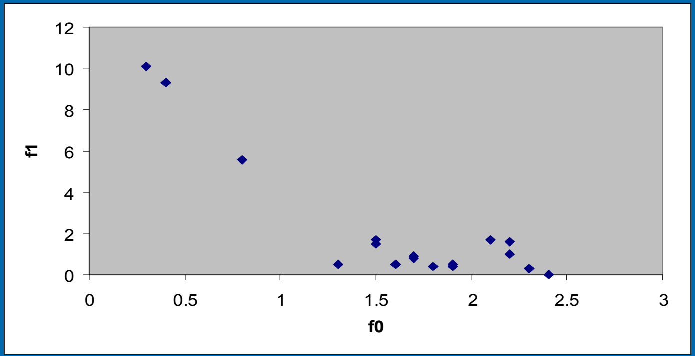


Figure4. A diverse set of good solutions belonging to different Pareto-Fronts is shown when only positive value for the stop to image distance is accepted.

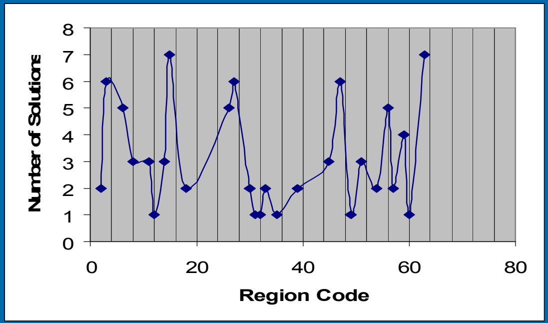


Figure3. Number of Solutions plotted against Region code. Show diversity explicitly.

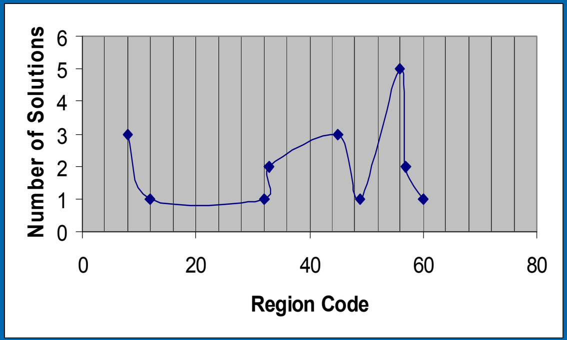


Figure5. Number of Solutions plotted against Region Code when only positive value for the stop to image distance is accepted. Show diversity explicitly.

PARETO- OPTIMA FROM NSGA2
Table1

NO	*CODE*	*F/#*	*SA*	*DST*
1	49	1.7	-0.84	1.9
2	56	4.4	-1.98	-0.44
3	60	2	-0.39	3.5
4	56	4.4	-2.3	-0.57
5	56	4.5	-1.97	-0.56
6	33	1.8	-1.72	0.94
7	56	4.5	-2.2	-1.7
8	8	5.4	-2.2	-1.1
9	33	1.69	-1.8	0.48
10	32	3.1	-1.57	-1.76
11	12	2.4	-0.43	9.4
12	45	1.73	-1.9	-0.49
13	57	2.1	-1.6	1.6
14	41	1.42	-2.5	-0.08
15	45	1.59	-2.3	-0.32
16	56	4.48	-1.97	-0.558
17	8	5.5	-1.6	-0.58
18	8	5.09	-1.4	0.55
19	57	2.09	-1.7	0.88

CODE V® AUTOMATIC DESIGN OPTIMIZATION
Table2

NO	*CODE*	*F/#*	*SA*	*DST*
1	49	3.4	-0.27	-2.8
2	57	17.8	-0.13	-1.36
3	61	12	-0.16	-3.1
4	57	16.5	-0.18	4
5	57	11.7	-0.23	-2.4
6	49	5.6	-0.22	-9.5
7	48	112.8	-0.1	2.4
8	9	19.1	-0.09	0.94
9	33	6.86	-0.42	-11.8
10	33	5.7	-0.47	-9.9
11	57	13.5	-0.23	-4.3
12	61	9.2	-0.28	-9
13	57	10.5	-0.27	-6.6
14	49	3.36	-0.38	-9.8
15	49	5.05	-0.24	-10.3
16	57	11.66	-0.23	-2.4
17	9	13.16	-0.09	0.28
18	9	15.9	-0.086	0.4
19	9	13	-0.08	0.62

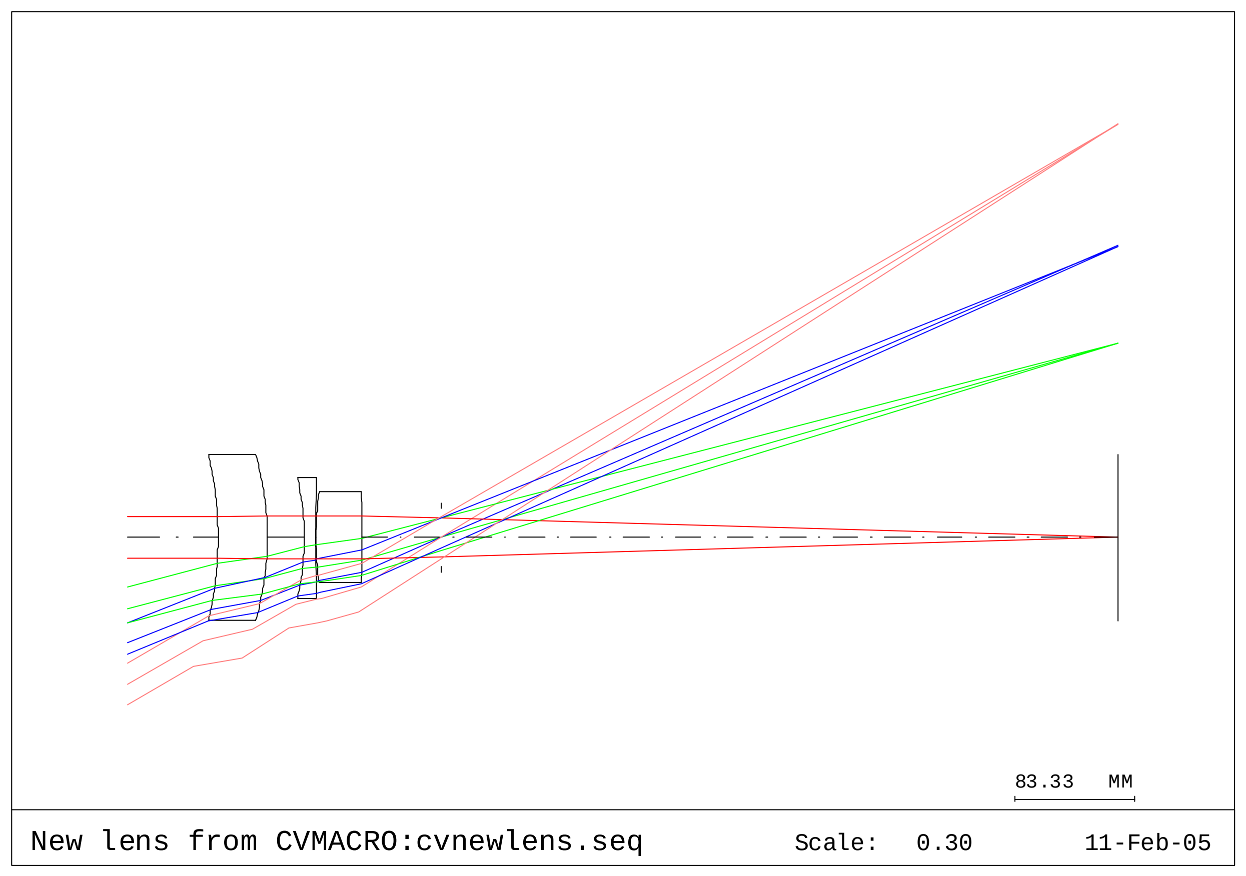
CODE V® GLOBAL SYNTHESIS Table3

NO	*CODE*	*F/#*	*SA*	*DST*
1	49	4.2	-0.21	-2.9
2	57	26.6	-0.09	2.3
3	57	21.9	-0.11	-1.43
4	57	19.5	-0.15	3.4
5	57	15.4	-0.2	-1.4
6	49	13.5	0.29	-15.4
7	48	193.1	-0.08	-5.9
8	9	15.5	-0.08	0.29
9	0	48.4	-0.16	6.1
10	0	44.6	-0.18	8.5
11	57	20.4	-0.18	-3.2
12	57	18.9	-0.18	-2.7
13	57	17.6	-0.19	-2.5
14	49	4.6	-0.36	-14.9
15	49	5.6	-0.19	-11.7
16	57	15.4	-0.2	-1.38
17	9	12.7	-0.08	0.32
18	9	14.3	-0.08	0.07
19	9	12.8	-0.08	0.33

Table4

NO	CODE	F:NO	EFL	BFL	OAL	SA	DST	Auto-OPT Code	F:NO	EFL	BFL	OAL	SA	DST	GLOBAL - OPT CODE	F:NO	EFL	BFL	OAL	SA	DST
1	49	1.7	48.3	31.8	132.7	-0.84	1.9	49	3.4	97.6	95.4	75.4	-0.27	-2.8	49	4.2	121.1	122.4	75.4	-0.21	-2.9
2	56	4.4	128.2	117.2	107.4	-1.98	-0.44	57	17.8	515.6	478.4	155	-0.13	-1.36	57	26.6	768.2	711	194.5	-0.09	2.3
3	60	2	58.4	37.4	110.2	-0.39	3.5	61	12	346.3	334.2	114.3	-0.16	-3.1	57	21.9	634.1	585.9	178.1	-0.11	-1.43
4	56	4.4	128	117.9	116.4	-2.3	-0.57	57	16.5	476.1	399	158.5	-0.18	4	57	19.5	562.1	482.4	176.4	-0.15	3.4
5	56	4.5	128.3	117.6	108.6	-1.97	-0.56	57	11.7	334.3	304.8	128.7	-0.23	-2.4	57	15.4	441.1	406.6	133.8	-0.2	-1.4
6	33	1.8	51.3	44.9	108.3	-1.72	0.94	49	5.6	160.3	166.2	63.8	-0.22	-9.5	49	13.5	386.2	425.1	89.1	0.29	-15.4
7	56	4.5	129.5	120.2	117	-2.2	-1.7	48	112.8	3231.3	3148.7	144.7	-0.1	2.4	48	193.1	5533.4	5473.1	144.3	-0.08	-5.9
8	8	5.4	155.8	138.2	118.6	-2.2	-1.1	9	19.1	548.4	501.2	86.6	-0.09	0.94	9	15.5	443.1	402.3	80.6	-0.08	0.29
9	33	1.69	48.3	43	118.8	-1.8	0.48	33	6.86	196.4	206.1	153.6	-0.42	-11.8	0	48.4	1387.4	1306.5	188.6	-0.16	6.1
10	32	3.1	88	81.4	122.3	-1.57	-1.76	33	5.7	163.3	170.4	132.6	-0.47	-9.9	0	44.6	1278.3	1190	150.9	-0.18	8.5
11	12	2.4	119.2	67.9	44.9	-0.43	9.4	57	13.5	388.2	365.3	132.8	-0.23	-4.3	57	20.4	584.1	548.2	156.8	-0.18	-3.2
12	45	1.73	49.6	47.9	111.1	-1.9	-0.49	61	9.2	263.7	262.4	122.1	-0.28	-9	57	18.9	541.2	506	151.3	-0.18	-2.7
13	57	2.1	59.9	50.6	123.3	-1.6	1.6	57	10.5	301.7	289.7	127.4	-0.27	-6.6	57	17.6	505.3	470.9	148	-0.19	-2.5
14	41	1.42	40.5	38.1	116.6	-2.5	-0.08	49	3.36	96.1	105	132.2	-0.38	-9.8	49	4.6	132.1	151.4	177.7	-0.36	-14.9
15	45	1.59	45.5	44	107.9	-2.3	-0.32	49	5.05	144.7	149.7	72.5	-0.24	-10.3	49	5.6	160.3	166.1	82.8	-0.19	-11.7
16	56	4.48	128.3	117.6	108.6	-1.97	-0.558	57	11.66	334.3	304.8	128.7	-0.23	-2.4	57	15.4	440.8	406.4	133.8	-0.2	-1.38
17	8	5.5	157.9	131.4	108.2	-1.6	-0.58	9	13.16	377.1	340.5	73.2	-0.09	0.28	9	12.7	364.9	329	72.1	-0.08	0.32
18	8	5.09	145.9	118.2	120.1	-1.4	0.55	9	15.9	455.8	414.3	81	-0.086	0.4	9	14.3	409.5	370.8	78.4	-0.08	0.07
19	57	2.09	59.8	53.0	114.8	-1.7	0.88														

LENS OBTAINED FROM THE SOLUTION WITH CODE=56 USING CODE V® LOCAL OPTIMIZER



ABERRATION COEFFICIENTS AND FIRST ORDER QUANTITIES FOR THE LENS OBTAINED FROM SOLUTION WITH

CODE=56

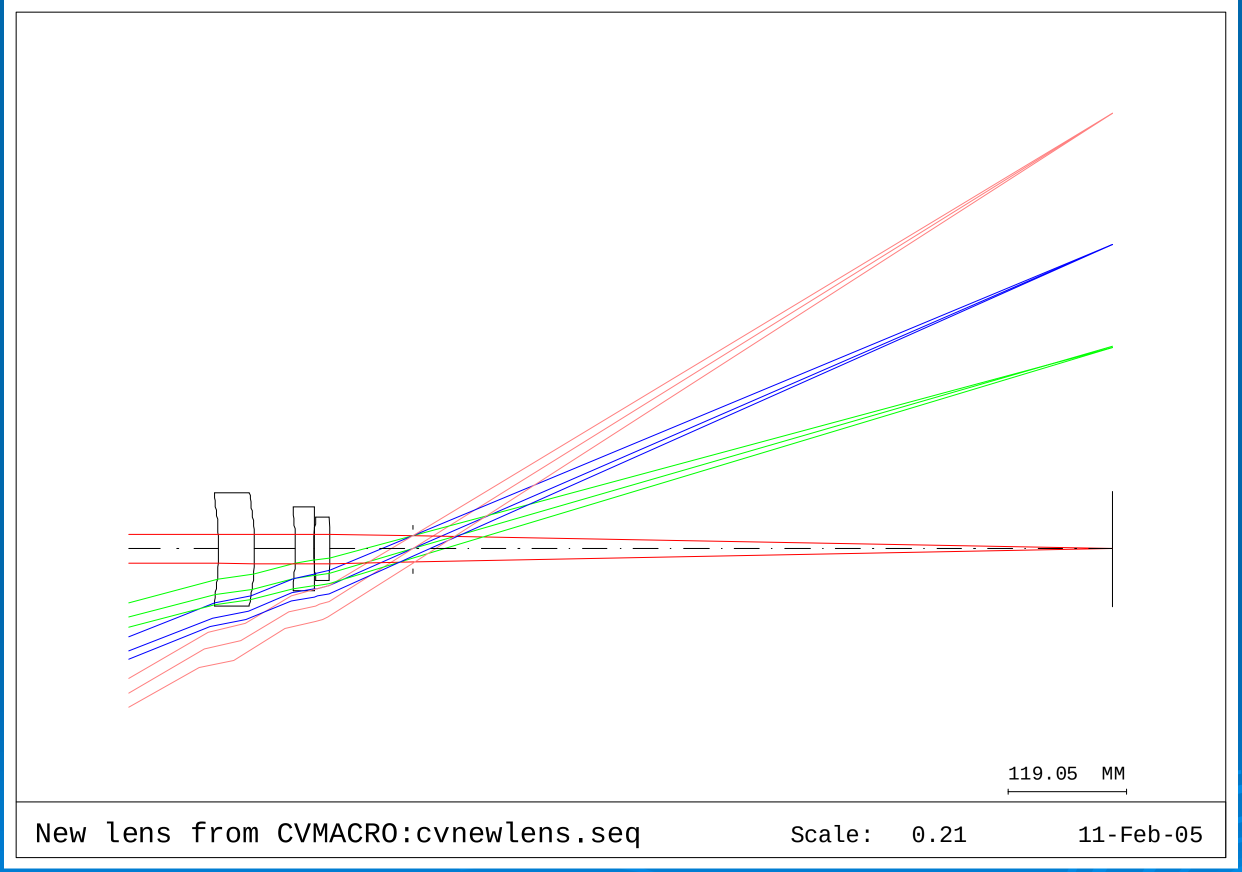
USING CODE V® LOCAL OPTIMIZER

- THO SO..I
- New lens from CVMACRO:cvnewlens.seq
- Position 1, Wavelength = 587.6 NM

	SA	TCO	TAS	SAS	PTB	DST	AX	LAT	PTZ
1	0.011020	-0.494049	9.020681	4.098682	1.637682	-61.250164	0.266459	-3.981934	0.001319
2	-0.030713	1.036604	-13.580869	-5.806042	-1.918629	65.320483	-0.371455	4.179028	-0.001545
3	0.040196	-1.187688	14.055969	6.257586	2.358395	-61.631177	0.855603	-8.426860	0.001899
4	0.020791	0.474080	3.864408	1.462198	0.261092	11.113664	0.543491	4.130891	0.000210
5	-0.153993	-0.941530	-4.365198	-3.085948	-2.446323	-6.289285	-1.038630	-2.116769	-0.001970
6	-0.016688	0.672163	-9.843243	-3.827030	-0.818923	51.380905	-0.465767	6.253293	-0.000660
STO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SUM	-0.129386	-0.440420	-0.848252	-0.900554	-0.926706	-1.355575	-0.210299	0.037650	-0.000746

- INFINITE CONJUGATES
- EFL 515.6163
- BFL 478.3903
- FFL -431.5708
- FNO 17.8434
- IMG DIS 468.2569
- OAL 154.9685
- PARAXIAL IMAGE
- HT 297.6912
- ANG 30.0000
- ENTRANCE PUPIL
- DIA 28.8968
- THI 124.1682
- EXIT PUPIL
- DIA 26.8105
- THI 0.0000

LENS OBTAINED FROM THE SOLUTION WITH CODE=56 USING CODE V® GLOBAL SYNTHESIS



ABERRATION COEFFICIENTS AND FIRST ORDER QUANTITIES FOR THE LENS OBTAINED FROM SOLUTION WITH

CODE=56

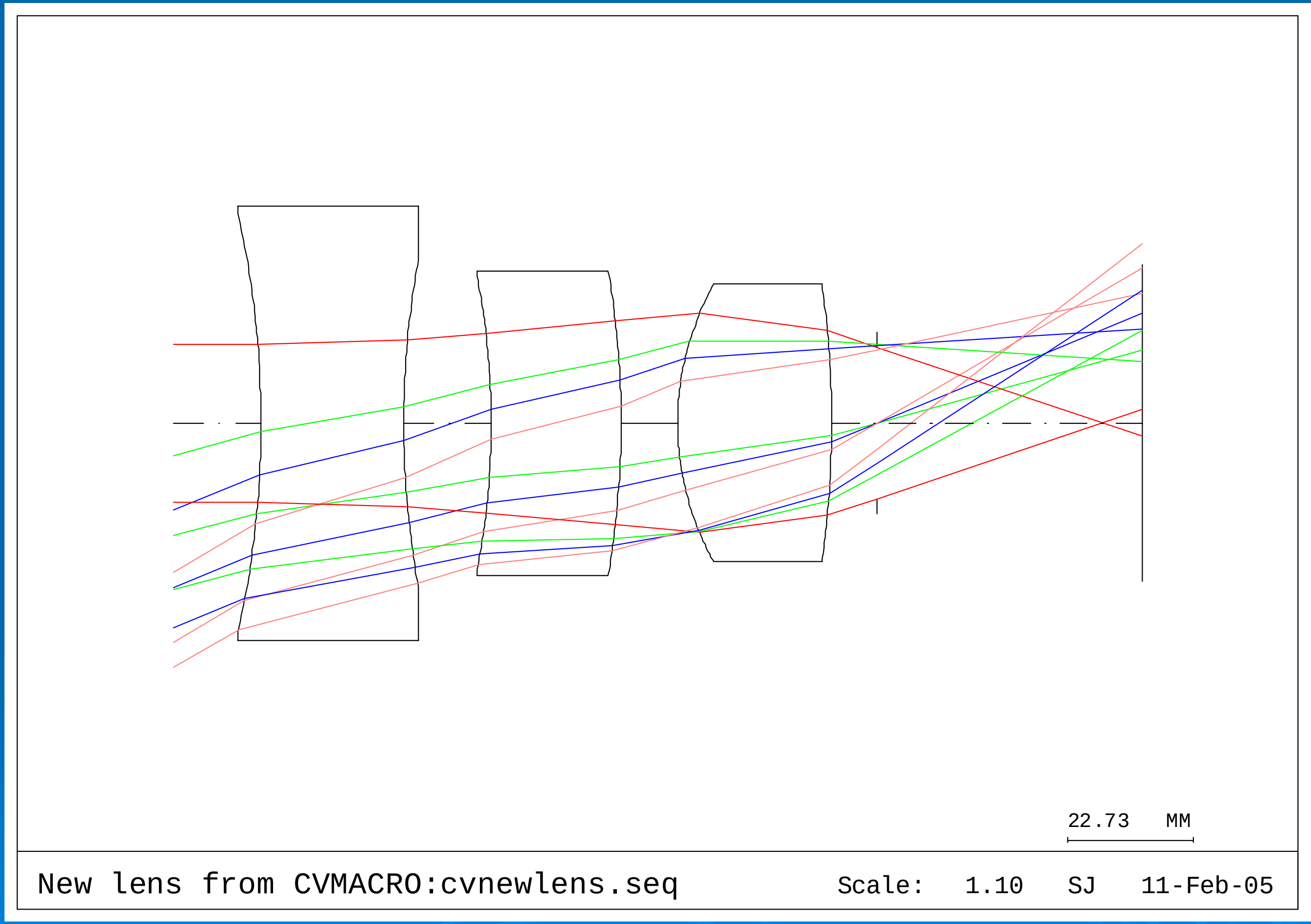
USING CODE V® GLOBAL SYNTHESIS

- THO SO..I
- New lens from CVMACRO:cvnewlens.seq
- Position 1, Wavelength = 587.6 NM

	SA	TCO	TAS	SAS	PTB	DST	AX	LAT	PTZ
1	0.005115	-0.329313	8.720887	4.009736	1.654160	-86.044872	0.269140	-5.775482	0.000894
2	-0.013670	0.680281	-13.233450	-5.710426	-1.948913	94.724885	-0.367343	6.093513	-0.001053
3	0.016567	-0.726833	12.958735	5.872490	2.329368	-85.880637	0.823572	-12.044106	0.001259
4	0.017526	0.456900	4.518974	1.871994	0.548505	16.267649	0.684117	5.944984	0.000296
5	-0.109020	-0.838960	-5.158552	-3.723841	-3.006486	-9.552245	-1.212876	-3.111220	-0.001625
6	-0.004556	0.325221	-8.218361	-3.059112	-0.479487	72.793838	-0.380161	9.046214	-0.000259
STO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SUM	-0.088038	-0.432704	-0.411767	-0.739159	-0.902854	2.308618	-0.183551	0.153904	-0.000488

- INFINITE CONJUGATES
- EFL 768.2492
- BFL 710.9513
- FFL -661.6422
- FNO 26.5859
- IMG DIS 699.9293
- OAL 194.4777
- PARAXIAL IMAGE
- HT 443.5489
- ANG 30.0000
- ENTRANCE PUPIL
- DIA 28.8968
- THI 168.5228
- EXIT PUPIL
- DIA 26.7416
- THI 0.0000

LENS SOLUTION WITH CODE=45



ABERRATION COEFFICIENTS AND FIRST ORDER QUANTITIES FOR THE LENS SOLUTION WITH

CODE=45

THO SO..I

New lens from CVMACRO:cvnewlens.seq

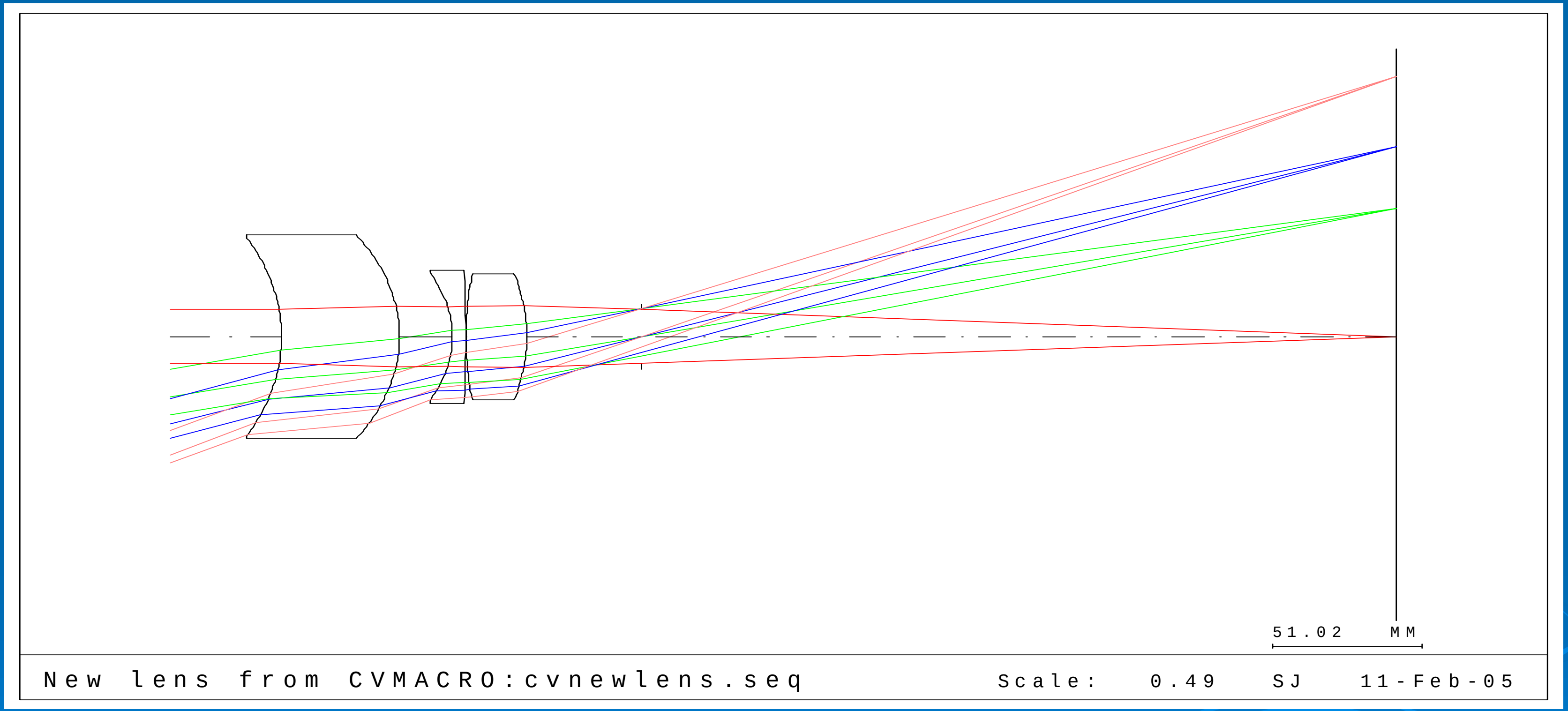
Position 1, Wavelength = 587.6 NM

	SA	TCO	TAS	SAS	PTB	DST	AX	LAT	PTZ
1	0.002907	-0.084319	1.035759	0.492239	0.220480	-4.759444	0.035873	-0.346856	0.001862
2	0.051995	0.201762	0.494792	0.320809	0.233817	0.414958	0.080785	0.104494	0.001975
3	-0.000701	0.035522	-0.288645	0.111384	0.311399	-1.881510	0.035484	-0.599396	0.002630
4	0.000537	-0.029847	0.289631	-0.078804	-0.263021	1.459147	-0.031393	0.581274	-0.002222
5	-1.091006	-0.710182	-1.168603	-1.065873	-1.014507	-0.231274	-0.540697	-0.117321	-0.008569
6	-0.907005	4.468263	-7.639238	-2.747586	-0.301760	4.511899	-0.371475	0.610011	-0.002549
STO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SUM	-1.943272	3.881199	-7.276305	-2.967830	-0.813593	-0.486224	-0.791422	0.232205	-0.006872

INFINITE CONJUGATES

EFL 49.5924
BFL 47.8571
FFL 11.5667
FNO 1.7311
IMG DIS 47.8579
OAL 111.0817
PARAXIAL IMAGE
HT 28.6322
ANG 30.0000
ENTRANCE PUPIL
DIA 28.6483
THI 62.9573
EXIT PUPIL
DIA 27.6458
THI 0.0000

LENS OBTAINED FROM THE SOLUTION WITH CODE=45 USING CODE V® LOCAL OPTIMIZER



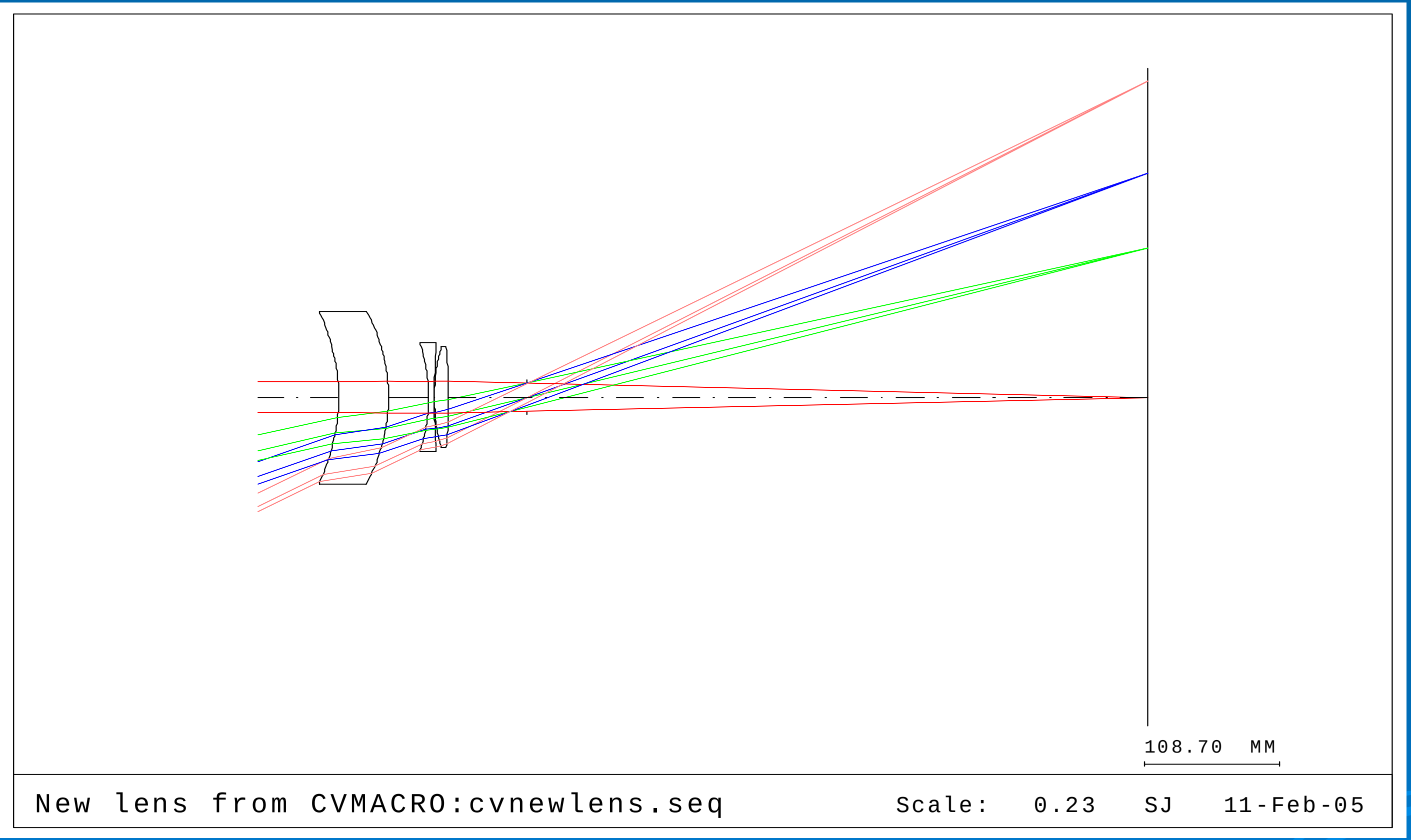
ABERRATION COEFFICIENTS AND FIRST ORDER QUANTITIES FOR THE LENS OBTAINED FROM SOLUTION WITH CODE=45 USING CODE V® LOCAL OPTIMIZER

THO SO..I
New lens from CVMACRO:cvnewlens.seq
Position 1, Wavelength = 587.6 NM

	SA	TCO	TAS	SAS	PTB	DST	AX	LAT	PTZ
1	0.046715	-1.170472	11.470749	4.953729	1.695219	-41.372463	0.275821	-2.303596	0.002692
2	-0.168264	2.820397	-17.715863	-7.210387	-1.957649	40.286110	-0.432731	2.417768	-0.003109
3	0.372249	-4.813055	23.711844	9.882693	2.968118	-42.593296	1.189944	-5.128527	0.004714
4	0.044355	0.671678	3.172780	0.912465	-0.217693	4.605904	0.431801	2.179631	-0.000346
5	-0.261138	-1.332722	-3.321427	-1.809967	-1.054238	-3.079066	-0.769208	-1.308555	-0.001674
6	-0.315862	4.030654	-19.231438	-7.801568	-2.086633	33.184779	-0.923343	3.927535	-0.003314
STO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
SUM	-0.281945	0.206480	-1.913355	-1.073036	-0.652876	-8.968032	-0.227715	-0.215744	-0.0010

INFINITE CONJUGATES
EFL 263.7445
BFL 262.4178
FFL -180.2502
FNO 9.2063
IMG DIS 256.1725
OAL 122.0984
PARAXIAL IMAGE
HT 152.2729
ANG 30.0000
ENTRANCE PUPIL
DIA 28.6483
THI 84.8277
EXIT PUPIL
DIA 28.5042
THI 0.0000

LENS OBTAINED FROM THE SOLUTION WITH CODE=45 USING CODE V® GLOBAL SYNTHESIS



ABERRATION COEFFICIENTS AND FIRST ORDER QUANTITIES FOR THE LENS OBTAINED FROM SOLUTION WITH

CODE=45

USING CODE V® GLOBAL SYNTHESIS

- THO SO..I
- New lens from CVMACRO:cvnewlens.seq
- Position 1, Wavelength = 587.6 NM

	SA	TCO	TAS	SAS	PTB	DST	AX	LAT	PTZ	
1	0.015743	-0.667133	11.328422	5.046124	1.904974	-71.277931	0.309949	-4.378120	0.001474	
2	-0.035690	1.167691	-14.834057	-6.344370	-2.099527	69.190034	-0.410041	4.471795	-0.001625	
3	0.039247	-1.142247	13.499954	6.112357	2.418559	-59.298426	0.889313	-8.627580	0.001872	
4	0.053895	0.762781	4.261929	1.862901	0.663387	8.788535	0.798254	3.765890	0.000513	
5	-0.240511	-1.120226	-4.542613	-3.383133	-2.803393	-5.252522	-1.243367	-1.930404	-0.002170	
6	-0.017003	0.694838	-10.356335	-4.046456	-0.891517	55.119311	-0.493421	6.721198	-0.000690	
STO	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	
SUM	-0.184320	-0.304297	-0.642699	-0.752577	-0.807516	-2.731000	-0.149313	0.022778	-0.000625	

- INFINITE CONJUGATES
- EFL 541.2048
- BFL 505.9707
- FFL -451.9176
- FNO 18.8913
- IMG DIS 497.0927
- OAL 151.3065
- PARAXIAL IMAGE
- HT 312.4647
- ANG 30.0000
- ENTRANCE PUPIL
- DIA 28.6483
- THI 126.9749
- EXIT PUPIL
- DIA 26.7832
- THI 0.0000

CONCLUSIONS

- I have successfully demonstrated the usefulness of NSGA2 for Optical System optimization.
- We can obtain alternate manufacturing choices for a given set of objective functions. This was demonstrated with Siedel aberration coefficients corresponding to spherical aberration and distortion chosen as objectives.
- Hybrid encoding is introduced for the radii of curvatures and they were found to be better suited for the present problem.
- Diversity is clearly evident in the solutions, which is a significant improvement over earlier studies by Ono.
- The diverse Pareto-Optimal front was used as a starting point for single objective local and global optimization methods. They resulted in a range of excellent and diverse solutions. Some of their features are shown in Tables 1-4.

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- U.K. Chakraborty & C.Z. Janikow, An analysis of Gray versus binary encoding in genetic search, Information Sciences, 156(3-4), 2003, pp. 253-269.
- http://www.iitk.ac.in/kangal/soft.htm

  This is the web site of K. Deb where NSGA2 was obtained.
- http://delta.cs.cinvestav.mx/~ccoello/EMOO/

  This site is maintained by Dr. Carlos A.Coello Coello. It is a repository of resources on Multi-objective optimization.

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