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Design of a twenty-element long focal length zoom lens

Robert M. Malone and Brent C. Frogget

EG&G, Inc., P.O. 809
Los Alamos, NM 87544

David A Grafton

Optical Systems Scientist, 427 Palisades Avenue
Santa Monica, CA 90402

Frank R. Mitchell

Frank Mitchell & Associates, 2130 Huntington Dr.
South Pasadena, CA 91303

ABSTRACT

An optical lens system with varying magnification has been designed for a 70-mm image format. Twenty optical elements were needed to provide for the 345- to 1050-mm focal length zoom range as well as the proper color correction over the visible spectrum. A 4-in diameter port window limits the *f/#* of the optical lens system. Operation of the lens system is done by actuating stepping motors through a MacPlus computer.

This lens system was designed for Los Alamos National Laboratory Group M-8, because no commercial zoom lens existed that would change its reduction from 1/15 to 1/4 at a focusing range of 5 meters. Additionally, we required a larger, non-standard image size that could be recorded by a rotating mirror streak camera. A Nikkor lens sales manual does offer a long focal length, 35-mm lens only upon special order. The closest focusing range of this Nikkor lens is 6 meters.

2. INTRODUCTION

Initially, a patent for a Nikkor zoom lens was used as a starting point for this current design.[1] Example 1 from this patent describes a zoom lens for a 35-mm still camera, with a focal length of 360 to 1,200-mm, and a relative aperture of F/11. No glass types were given in this patent.

After 67 design iterations using the CODE V™ lens design program[2], we reached our best zoom lens system. The exit pupil of the zoom lens was controlled so that it would match the entrance pupil of an existing rotating mirror streak camera lens system. Fig. 1 shows 5 different zoom magnification positions from this final system. Twenty glass elements make up the zoom lens which operates from 345 to 1050-mm effective focal lengths. The first element shown in Fig 1 is an additional port window that the lens system must look through. The last element is an additional window mounted onto the back end of the housing box to keep the dust out. There are five groups of optical elements that move during magnification changes. The image plane is kept fixed during magnification changes, so that the Streak Camera can remain stationary during data recording. A variable stop is mounted onto the 5th optical group and can be reached through a port in the top of the lens housing. The zoom lens prescription and some of the zoom lens specifications are listed in Table 1. In this table, the last dust protective window is not listed.

In general, lens designs fall into "infinite" or "finite" conjugates. Reduction or magnification ratios that are numerically 0.166 (6:1) are considered to be in the infinite range. Most photographic objectives are well within this range. Reduction ratios in the .20 to .25 (4:1) range transcend the infinite range and become in the muddy finite conjugate range. In general, it is more difficult to maintain performance at these lower magnification ratios. In Fig. 1, the short EFL zoom position operates at 15:1 while the long EFL zoom position operates at 4:1.

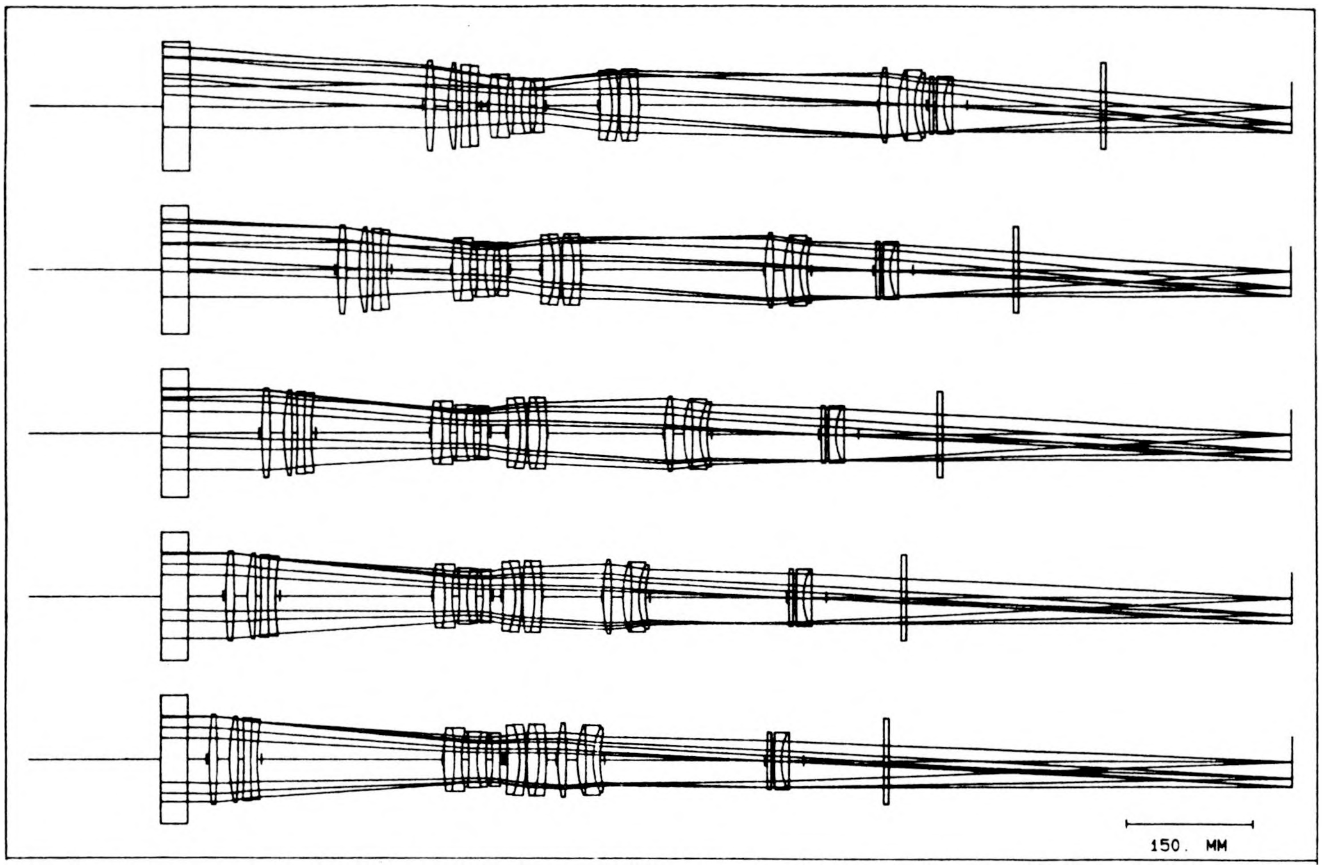

Fig. 1. Layout of 5 different positions for the zoom lens. Starting from the top is shown: 349-mm, 512-mm, 739-mm, 918-mm, 1045-mm Effective Focal Lengths (EFL).

All 5 optical groups are mounted inside of a protective housing box. Movement of all optical groups is accomplished by mounting each optical group on a rail-bearing slide. Each rail is powered by a stepping motor under computer control. The first lens group is mounted to the front wall of the box. So, to move this first lens group, the entire box must move. All other lens groups move within this housing box. A continuous plotting of lens position versus magnification change for all lens groups is shown in Fig. 2. A weighted error function is also been added to Fig. 2 to indicate how resolution decreases at the short and long focal lengths. The front group performs most of the focusing adjustment (with some compensation of the fourth group). That means that the entire housing box moves during small focus changes. After several focus changes have been made, it is practical to reset the magnification by running all step motors through their cycles again.

3. DESIGN

As a lens approaches being diffraction limited, both axial and more especially lateral chromatic aberrations limit the performance. For this zoom lens, the approach taken was to introduce early into the design FK51 as a major glass with which to combat both of these aberrations. This glass has extreme anomalous dispersion characteristics which may be combined with several "near normal"glasses to produce near apochromatic corrections. The KZFSN4 glass was also frozen at an early stage for the same reason as the FK51. The computer allowed the remainder glasses to vary. The remainder glasses were each fixed one at a time by trial and error, preserving the five zoom position error function. The last glasses (as always) are difficult to find, but eventually BALF50 and BAF12 provided a suitable combination.

The Modulation Transfer Function (MTF) data for one zoom position is given in Fig. 3. This data shows that the zoom lens system is nearly diffraction limited over the designed range of magnifications. This analysis has also been carried out

Surface number	Radius (mm)	Thickness airspace (mm)	Glass type	Diameter (mm)
OBJ:	INFINITY	5000.000000		
1:	INFINITY	31.750000	BK7_SCHOTT	152.4
2:	INFINITY	25.400000		
3:	457.20000	10.000000	FK51_SCHOTT	100.0
4:	-602.31020	14.894096		
5:	225.17100	10.000000	FK51_SCHOTT	95.3
6:	-1023.31520	6.587436		
7:	-875.61420	8.000000	LAF2_SCHOTT	91.4
8:	818.13400	8.000000	SK5_SCHOTT	89.3
9:	280.89860	12.300203		
10:	245.44020	12.357668	SF1_SCHOTT	70.0
11:	-241.85880	8.000000	SK5_SCHOTT	67.8
12:	145.08480	8.589332		
13:	-298.32300	8.638408	FK51_SCHOTT	61.5
14:	108.00080	10.000000	BALF50_SCHOTT	59.7
15:	243.48440	7.912263		
16:	-151.76500	8.041868	PK2_SCHOTT	58.7
17:	457.20000	66.363487		
18:	-518.61720	14.081288	SK16_SCHOTT	74.6
19:	-117.14480	7.620000	F4_SCHOTT	76.4
20:	-223.57080	0.734060		
21:	301.62500	14.092639	FK51_SCHOTT	79.2
22:	-167.89400	8.287114	SF4_SCHOTT	79.1
23:	-413.11830	280.115750		
24:	189.73800	10.000000	KF9_SCHOTT	82.6
25:	-645.76960	12.753638		
26:	119.78640	10.292271	FK51_SCHOTT	77.5
27:	-1023.31520	8.000000	LAF2_SCHOTT	76.3
28:	90.29700	8.000000	BAF12_SCHOTT	71.4
29:	120.65000	4.913485		
STO:	INFINITY	4.082857		
31:	724.07780	5.000000	K10_SCHOTT	63.3
32:	INFINITY	3.657600		
33:	724.07780	8.000000	KZFSN4_SCHOTT	63.1
34:	74.14260	9.517139	F5_SCHOTT	62.7
35:	1123.44200	396.049148		
IMG:	INFINITY	-0.031792		

	position 1	position 2	position 3	position 4	position 5
EFL (mm)	349	512	739	918	1045
reduction	0.064	0.097	0.148	0.200	0.250
EPD (mm)	54	74	106	131	144
$f/\#$	6.7	7.7	8.8	10.2	12.8
Field of view in degrees	± 4.5	± 3.0	± 1.8	± 1.2	± 0.9
image distance (mm)	399	460	523	560	661
Distortion	0.038	-0.001	-0.018	-0.027	-0.034
MTF % @ 40 lp/mm	>65	55	50	50	40
MTF % @ 60 lp/mm	>50	45	40	40	25

Design wavelengths = 656.3, 587.6, and 435.8-nm, with weights of 1 1 1

Table 1. Design data of the zoom lens.

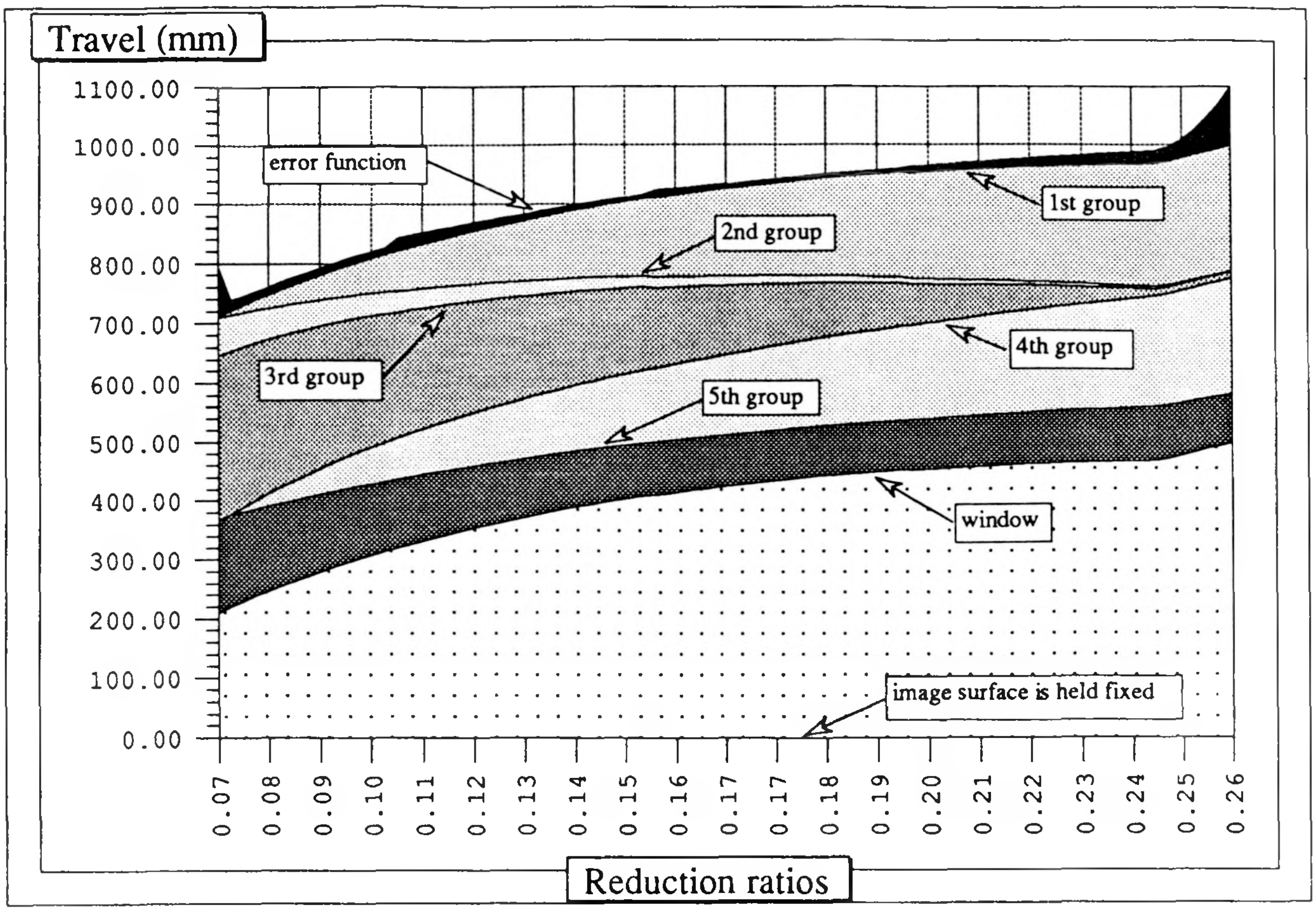

Fig. 2. Lens group motions. Error function is almost constant across this range of reduction ratios.

for many zoom positions with similar MTF response. MTF data has also been collected at different object distances (4, 5, and 6 meters).

Special care was taken in the housing design to eliminate dust from the optical surfaces and the lead screws. The housing box is made up of 1/2 inch black anodized aluminum plates. A system layout showing lens housing, computer, and some electrical controls is shown in Fig. 4. The limit switches keep the lens groups from crashing in to each other. The home switch is used if the operator does not know the current locations of the lens groups (this could occur during power off situations).Power off brakes are used on all rail slides to freeze a lens group's position after it has been moved. Software programs control the movement of the lens groups. An operator inputs the effective focal length desired and the software will call upon the Lookup Table to locate the positions of the lens groups. The step motors will run through a predetermined sequence to move all lens groups to their new desired locations. Fine focusing of the zoom lens system is performed with the arrow keys of the MacPlus computer.

4. TOLERANCE ANALYSIS

The whole lens design was fitted to glass melt data prior to fitting to test plates. Radii tolerances were 3 fringes on the test plate fit or ± 0.1%, which ever was the most stringent. Irregularity was 1/4 wave over the clear aperture. Total Indicator Runout (TIR) was called out at 0.0004". Thickness and air spaces were set to ±0.002". All of these tolerances were introduced into the zoom lens via the TOR program (a utility within the CODE V™ lens design program[2]). Since this was to be a custom designed lens, the measured test plate fit errors were computed. The true radii and measured thickness data were reintroduced into the zoom lens prescription prior to making the final assembly data runs.

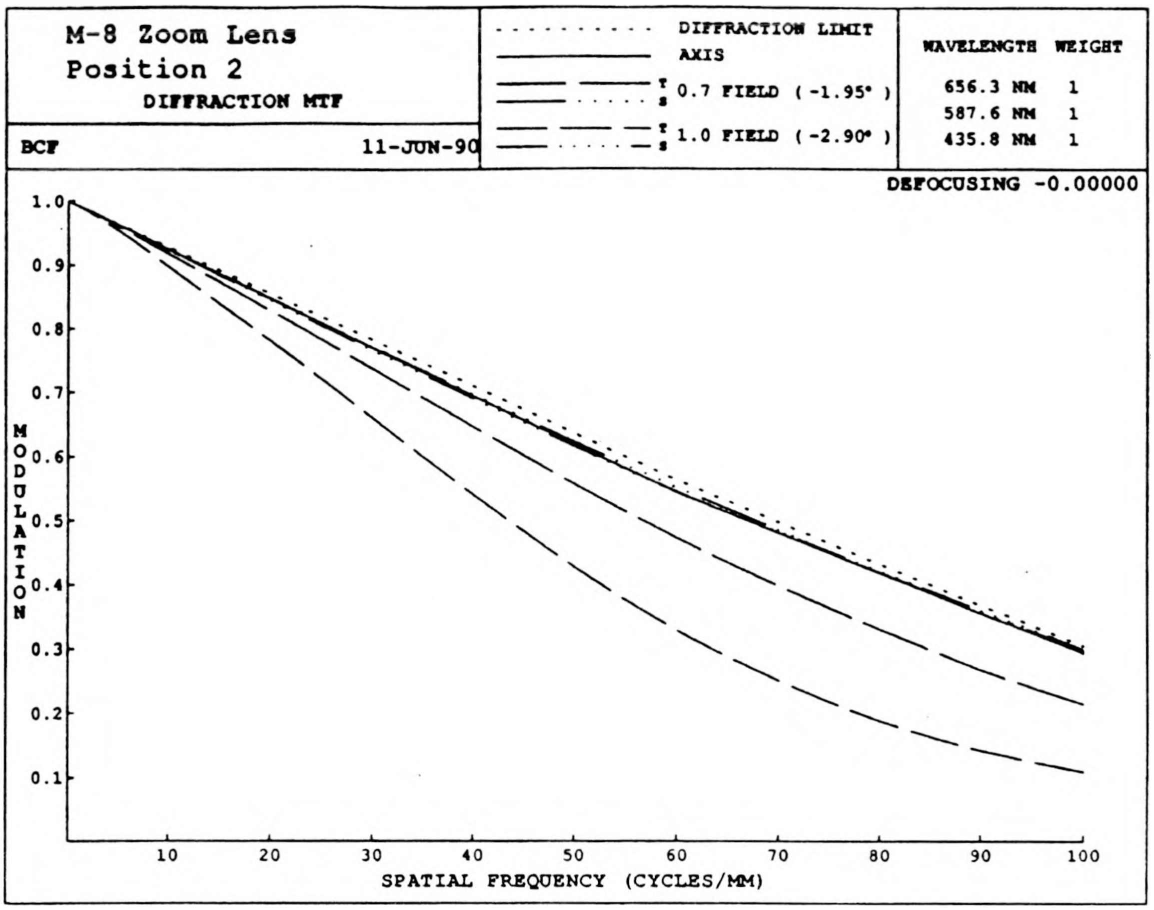

Fig. 3. Polychromatic MTF curves of the zoom lens for position 2, which has 512-mm EFL.

The lens elements were mounted into 5 group housings. Each of the lens groups was independently tested on an optical bench for proper focus and concentration. After we were satisfied with the performance of each of the lens groups, the complete system alignment process became straight forward. A HeNe laser passed light through fine pin hole apertures that were mounted onto the front surface of each optical group. Additionally, each of the five mechanical group housings has a reference surface that an optical flat can be mounted to. Each of the lens group was cycled back and forth (automatically, under computer control) while concentration adjustments are made. Tolerance on slide tracking of each group was kept to ±0.002 inches over a distance of 4 inches travel.

5. CONCLUSION

The paper is of interest to those who work with long focal length zoom lenses. This zoom lens could be used to record images on the 70-mm films that are used in the movie industry. This lens was designed for high speed photography within the visible wavelength range. Because this zoom lens is computer controlled, reproducing past setups and magnifications is not dependent on a skilled operator.

This lens is intended to operate in the horizontal position. Another version of this zoom lens system will operate in the vertical direction. Every care was taken so that this first lens system could be retrofitted to also operate in the vertical direction. Thus, extra-heavy duty rail-bearing slides and motors were used. This also increased the weight of the lens to about 200 lbs.

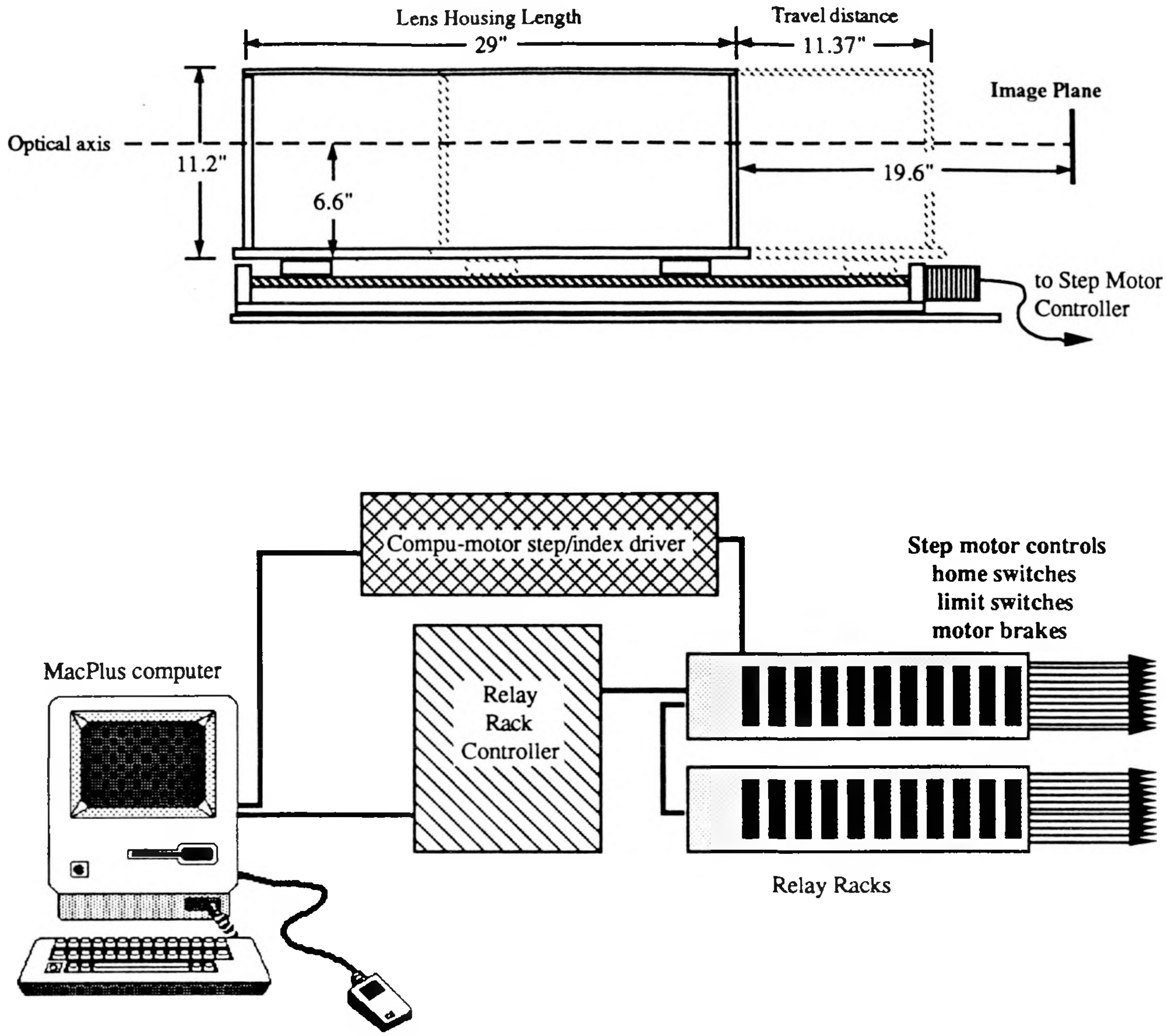

Fig. 4. Hardware layout of zoom lens system.

6. ACKNOWLEDGEMENT

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7. REFERENCES

1. Nakamura, Soichi, "Optical System for the Magnification Varying Portion of an Ultra-Telephoto Type Zoom Lens", *patent number 3,743,384*, assigned to Nippon Kogaku K.K, July 3, 1973.
2. CODE V™ lens design program, (Optical Research Associates, 550 N. Rosemead Boulevard, Pasadena, CA 91107).