Endoscope Design

Section A

Objective Focal Length f_O = 6.667 mm

Imaging Focal Length f_I = 6.429 mm

Field Lens Focal Length f_F = 5.0 mm

Number of Field Lenses = 14

Relay Focal Length f_R = 5.0 mm

Number of Relay Lenses = 13

Total Number of Lens Elements Required = 29

Total System Length (Objective Lens to the CCD Array) = 298 mm

Section B

CCD Location Relative to the Imaging Lens = 25.71 mm

Unvignetted Object FOV = 2.50 mm

Does the image of this object FOV underfill or overfill the CCD?

FOV_I = 4.28 mm

Overfills

Endoscope

To begin the design, consider the objective lens:

object: ± 2 mm $\quad h = 2$ mm

stand off: 20 mm $\quad z_o = -20$ mm

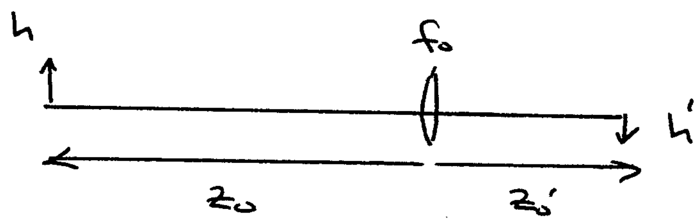
For the image to fit within the tube

image = ± 1 mm $\quad h' = -1$ mm

$$m = h'/h = -1/2 = z_o'/z_o$$

$$z_o' = -1/2\, z_o$$

$$\underline{z_o' = 10 \text{ mm}}$$



$$\frac{1}{z_o'} = \frac{1}{z_o} + \frac{1}{f_o}$$

$$\underline{f_o = 6.667 \text{ mm}}$$

Use a series of field and relay lenses to transfer this image down the tube.

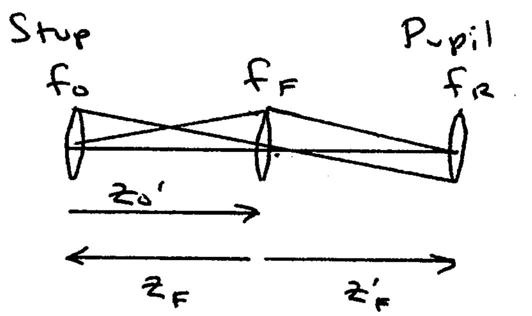
Field Lenses – image stops and pupils

Relay Lenses – re-image intermediate images

First Field Lens – located at the first image.

The field lens images the stop/objective to the next pupil (where the first relay lens is located).

The stop image should fill the tube.



$z_F = -z_o' = -10\,mm$

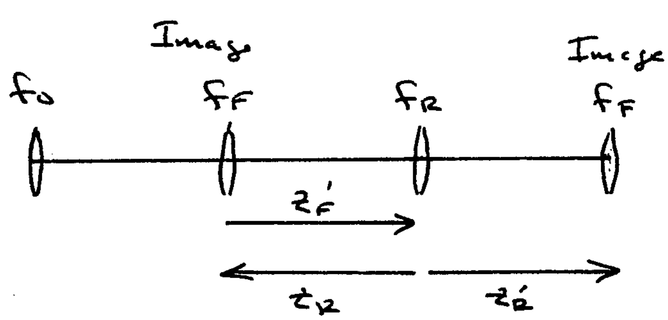
Since the stop and pupil are both 2 mm in diameter, the field lens works at 1:1 conjugates

$m_F = -1$

$z_F' = -z_F = 10\,mm$

$f_F = 5\,mm$

The first relay lens now re-images the intermediate image at the field lens at 1:1 conjugates



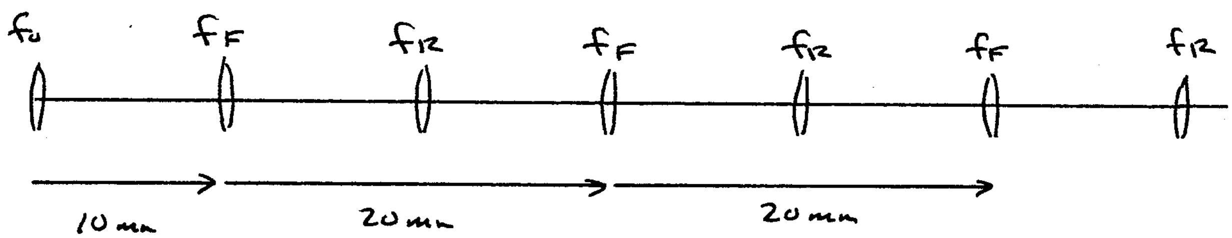
$z_R = -z_F' = -10\,mm$

$z_R' = -z_R = 10\,mm$

$f_R = 5\,mm$

The next field lens is located at this image formed by the relay lens. There is no vignetting since the field lenses are at image planes.

A series of relay and field lenses all working at 1:1 conjugates transfers the image and pupils down the tube.



The distance from the objective lens to an intermediate image is determined by the number N of relay-field stages:

$$L_{INTER} = z_o' + N\,(z_F' - z_R)$$

$$L_{INTER} = 10\,mm + N\,(20\,mm)$$

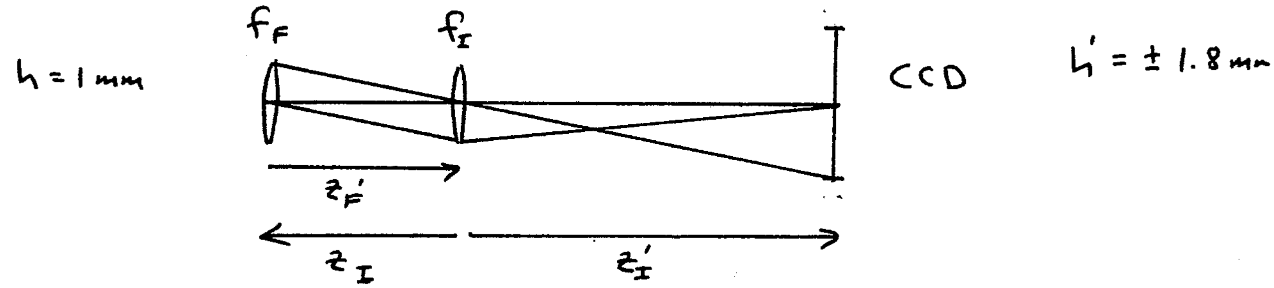
In order to determine N, the final relay lens – actually the imaging lens – must be defined.

CCD Array: 3.6 mm × 4.8 mm

The final image must fit within the CCD area.

$$h_I' = \pm 1.8\,mm$$

The imaging lens follows the final field lens:



Since the field lens is the same as all the other field lenses — $z_F' = 10$ mm

Relay the pupil to the imaging lens (also 2mm diameter):

$$z_I = -z_F' = -10 \text{ mm}$$

$$m_I = -\frac{1.8 \text{ mm}}{1.0 \text{ mm}} = \frac{z_I'}{z_I}$$

$$\underline{z_I' = 18.0 \text{ mm}}$$

$$\frac{1}{z_I'} = \frac{1}{z_I} + \frac{1}{f_I}$$

$$\underline{f_I = 6.429 \text{ mm}}$$

All of the lenses and spacings have now been specified. The final image (at the field lens) to the CCD distance is

$$L_I = -z_I + z_I' = 28.0 \text{ mm}$$

To determine the number of field-relay stages, use the overall system length requirement

$$280\ mm < L < 300\ mm$$

$$L = L_{INTER} + L_I$$

$$L = 10\ mm + N(20\ mm) + 18\ mm$$

$$L = 38\ mm + N(20\ mm)$$

$N = 13$ Stages of relay-field lenses

Total Length $L = 298\ mm$

Number of Lenses: Objective Lens
First Field Lens
13 Stages of Relay-Field Lenses
Final Imaging Lens

Obj - F (RF)(RF)(RF)(RF)(RF)(RF)(RF)(RF)(RF)(RF)(RF)(RF)(RF) I

29 Total Elements

$f_O = 6.667\ mm$ $f_F = 5.0\ mm$ (Qty 14)

$f_I = 6.429\ mm$ $f_R = 5.0\ mm$ (Qty 13)

While not required, the paraxial raytrace of this system is attached. Because of the repetitive nature of the system, not all relay-field stages need to be traced. Only 2 are shown.

Part A 20 mm Stand-Off Distance

	Obj	Stop								
		f_o	f_F	f_R	f_F	f_R	f_F	f_I	CCO	
Surface	0	1	2	3	4	5	6	7	8	9
f		6.667	5.0	5.0	5.0	5.0	5.0	6.429	—	
$-\phi$		-0.15	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1556		
t	20	10	10	10	10	10	10	18		
Marginal Ray										
y	0	1.0	0	-1.0	0	1.0	0	-1.0	0	
u	0.05	-0.1	-0.1	0.1	0.1	-0.1	-0.1	0.0556		
Chief Ray										
$\bar{y}$	2.0	0	-1	0	1	0	-1	0	1.8	
$\bar{u}$	-0.1	-0.1	0.1	0.1	-0.1	-0.1	0.1	0.1		
y										
u										

Part B - The same endoscope design is used with an object at 15 mm. The CCD is shifted to obtain focus. Use a paraxial raytrace - once again not all of the relay-field stages must be done - only 2 are shown on the attached raytraces.

The marginal ray determines the new CCD location.

$y_0 = 1$ mm at the objective lens

Imaging Lens - CCD Distance = 25.71 mm

Trace a potential chief ray to determine vignetting and FOV. Here, $\bar{y}^*$ at the object is 1.0 mm

Note that the pupils continue to be re-imaged at each relay lens. This is not surprising as only the object location changed.

The FOV will be limited by vignetting at the field lenses:

Marginal Ray $y_F = \pm 0.1667$ mm

Potential Chief Ray $\bar{y}_F^* = \pm 0.6667$ mm

This chief ray is scaled to satisfy the condition for an unvignetted FOV

$$a_F = |y_F| + c|\bar{y}_F^*| = 1.0 \text{ mm} \quad \text{(field lens radius)}$$

For this potential chief ray, the scaling factor is

$$c = 1.25$$

The final chief ray is now obtained.

Part B

15 mm Stand-Off Distance

Same element positions as Part A; CCD shifted

Surface	0 (Object)	1 (Stop f_0)	2 (f_F)	3 (f_R)	4 (f_F)	5 (f_R)	6 (f_F)	7 (f_I)	8 (CCD)	9
f		6.667	5.0	5.0	5.0	5.0	5.0	6.429	–	
$-\phi$		-0.15	-0.2	-0.2	-0.2	-0.2	-0.2	-0.1556		
t	15	10	10	10	10	10	10	? (25.71)		
Marginal Ray										
y	0	1.0	0.1667	-1.0	-0.1667	1.0	0.1667	-1.0	0	
u	0.0667	-0.0833	-0.1167	0.0833	0.1167	-0.0833	-0.1167	0.0389		
Potential Chief Ray										
$\bar{y}^*$	1.0	0	-0.6667	0	0.6667	0	-0.6667	0	1.714	
$\bar{u}^*$	-0.0667	-0.0667	0.0667	0.0667	-0.0667	-0.0667	0.0667	0.0667		
Chief Ray										
y	1.25	0	-0.8333	0	0.8333	0	-0.8333	0	2.142	
u	-0.0833	-0.0833	0.0833	0.0833	-0.0833	-0.0833	0.0833	0.0833		

Chief Ray Scale Factor = 1.25

From the raytrace –

The unvignetted object FOV:

$$\bar{y}_o = \pm 1.25 \text{ mm} \qquad FOV_o = 2.50 \text{ mm}$$

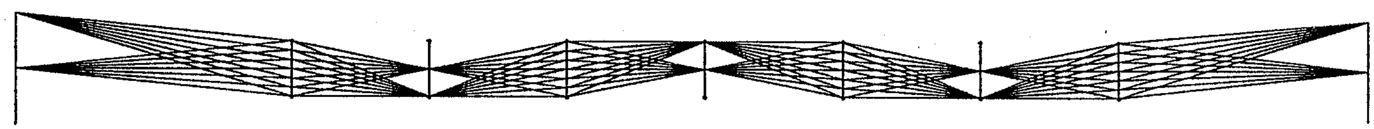
The corresponding image size at the CCD:

$$\bar{y}_I = \pm 2.142 \text{ mm} \qquad FOV_I = 4.284 \text{ mm}$$

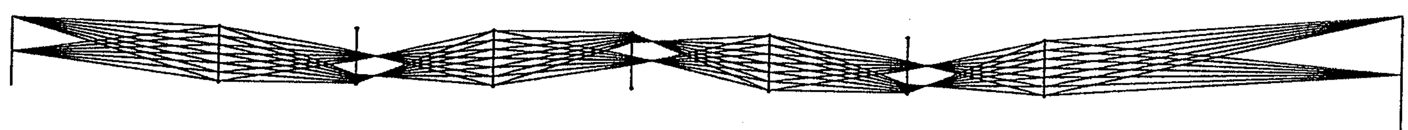
Since this image size is larger than the CCD height of 3.6 mm, the unvignetted FOV overfills the CCD array.

Ray drawings of the system used with the two object positions are also attached.

Part A - Object at 20 mm



Part B - Object at 15 mm



Note that the intermediate images are displaced from the field lenses.