A tutorial for designing fundamental imaging systems

Koichi Taniguchi

OPTI 521 – Distance Learning
College of Optical Science
University of Arizona
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１． Abstract

This tutorial shows what to do when we design opto-mechanical system for imaging system. Basic principles about designing paraxial systems are introduced. In particular, you can find how to decide specifications, how to select optical elements, how to calculate image shift and how to estimate wavefront errors.

２． Introduction

Optical elements have been developed due to development of manufacturing tools, and we can use various kinds of mirrors, lenses, prisms or filters in various systems, and we can get high-quality elements. When we develop optical systems, we need to decide specifications according to cost, size or image quality.

Figure.2.1 is an example of imaging microscope optical system. This includes features which we have to decide when we are designing basic optical systems.

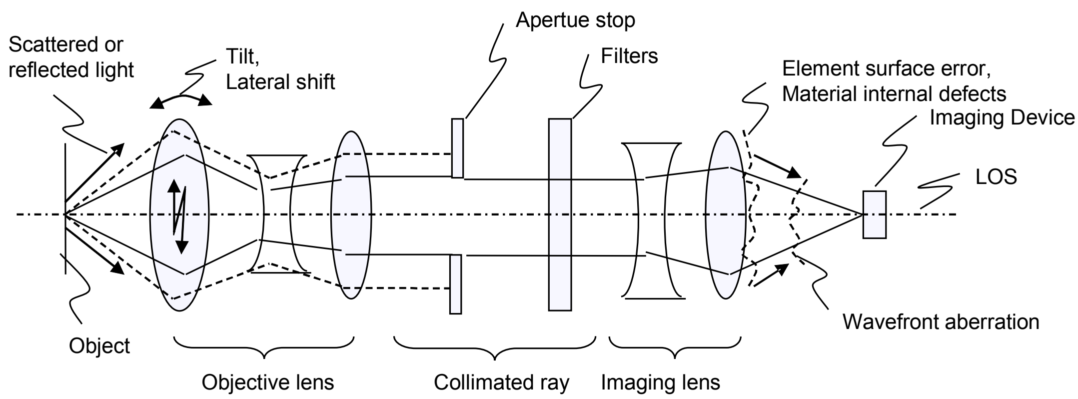


Figure.2.1 An example of imaging microscope optical system

３． Specifications of optical system with imaging devices

When we design optical systems, we need to decide specifications of optical systems. We need to decide following basic specifications, (1) Magnification and focal length, (2) Resolution and depth of focus.

(1) Magnification and focal length

We should decide magnification of designed system according to the resolution of the image. We should decide it at first. Magnification for fundamental optical system is shown in Figure.3.1. There are 2 lenses and object with height of h_o. Object is placed at front focal plane of an objective lens, and an image is given at back focal plane of an imaging lens. Magnification of this optical system $\boldsymbol{m}$ is given by the following equation[1]. This shows that we can calculate back focal length $\boldsymbol{f_i}$ after we decide front focal length $\boldsymbol{f_i}$ and magnification $\boldsymbol{m}$.

The distance between the objective lens and imaging lens need not to be $\boldsymbol{f_o+f_i}$ because the ray is collimated between the 2 lenses. The image height is independent of this distance.

$$m = \frac{h_i}{h_o} = \frac{f_i}{f_o} \rightarrow f_i = m \cdot f_o$$

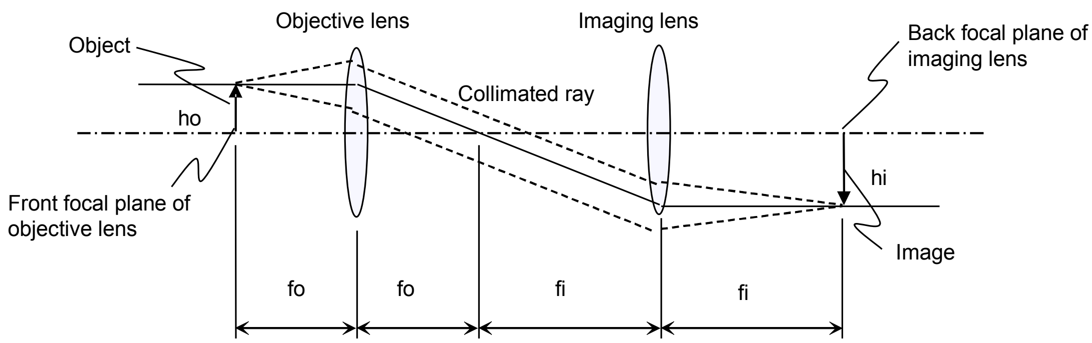


Figure. 3.1 The fundamental optical system with 2 lenses

(2) Resolution and depth of focus (DoF)

Resolution and depth of focus (DoF) depend on system F#. F# is important factor for image brightness and resolution of optical system, which is defined by following equation. We can get higher resolution with larger F#, but the depth of focus (DoF) becomes shorter. We have to balance both the DoF and resolution. There are 2 pictures taken with different F# in Figure.3.2. The background is focused in The picture because the camera with large F# has long DoF. On the other hand, the background is defocused in the picture because the camera with small F# has short

DoF. We use aperture stop in order to control F#.

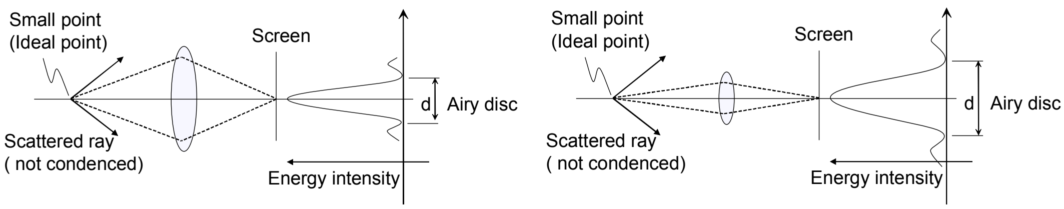
$$F\# = \frac{f}{D}$$

Where ***f*** is the focal length of optical element, and ***D*** is the diameter. Resolution is also decided with F#. We can get high resolution with small F#. The resolution is described with Airy disc, explained in Figure.3.3. Airy disc is the size of image of a small point. The size of Airy disc is given by following equation. The resolution of optical system is often described by the Airy disc.

$$d = 2.44F \cdot \lambda$$

Where d is diameter of Airy disc. Resolution is a minimum distance in which two points can be distinguished, which is explained in figure.3.4. Resolution is almost the same size as the size of the Airy disc.

Figure.3.2 Picture with large F#(left, f5.6)　and with large F#(right, f/32)
(Image by Wikipedia)



Small Airy disc with large lens　　Large Airy disc with small lens

Figure3.3. Airy disc

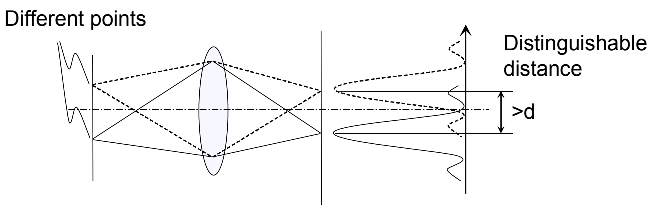


Figure.3.4 Resolution of optics and Airy disc

4． Optical elements

After we decide optical specifications, we need to think of what optical elements to use.

(1) <u>Lens, mirrors and prisms</u>

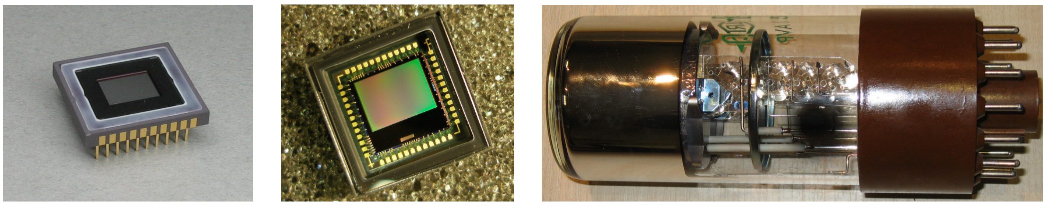
Lens, mirrors and prisms are most basic optical elements. These deviate rays and we can condense rays or rotate images. At first we decide what lens to use and calculate focal length or other basic features.

(2) <u>Image sensor (Photo detector)</u>

Image sensor transfers light energy to electrical energy. There are various kinds of sensors such as CMOS and CCD sensors, and it provides with each merit.[3][8] CCD or CMOS sensor is used for imaging devices such as digital camera or digital photo copier. PMT is a very high sensitivity photo detector which is used for detection few photon.[8] Table.4.1 shows merit and demerit of each sensor. We usually use CCD area sensors for imaging systems. CCD, CMOS image sensor and PMT is shown in Figure.4.1. CCD and CMOS is almost the same size, but PMT is much larger.

Table.4.1 Image sensor type

	Merit	Demerit
CCD(charge coupled device)	high sensitivity, low noise	high power consumption, high driving voltage, various power supply, difficult to manufacture
CMOS(complementary metal oxide semiconductor)	low power consumption, easy to manufacture, no smear	low sensitivity, fixed patteren noise,
PMT(photo multiplier)	very high sensitivity	larger than CCD or CMOS,



(a) CCD　　(b) CMOS　　(C) PMT

Figure.4.1 Image sensors (Photo detectors)

(Image by Wikipedia,Hamamatsu)[3][8]

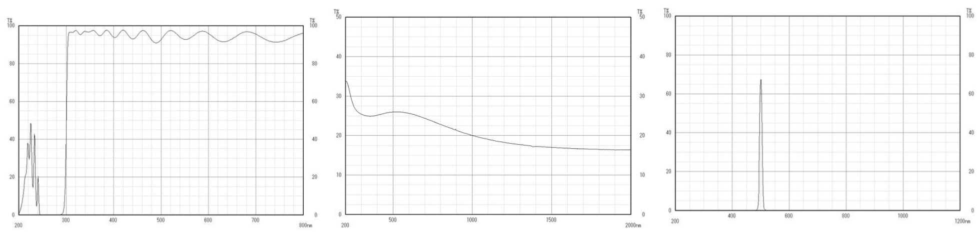
(3) <u>Filters</u>

Filters are used to attenuate specific wavelength of rays. We should use filters when we want to control brightness or colors of images, or need to detect specific wavelength.

There are various kinds of filters such as band-pass filter that attenuate excluding specific wavelength rays.[3] ND filter attenuates thoroughly over a wide wavelength band, so we can control amount of rays without changing system F#. Sharp cutting filters that cut outside inferred ray or outside. Because of these features, these filters look like colored glass window. Light transmission spectrum of each filter is shown in Figure.4.2.

PL(polarized light) filter can pass a specific polarized light, which is used to suppress reflected light and you can see them used for sunglasses or camera filter which can suppress reflected light from surface of water or other reflective surfaces.

We can find many other filters from optical components manufacturer website and need to choose appropriate filters according to our purpose.[4]-[6]



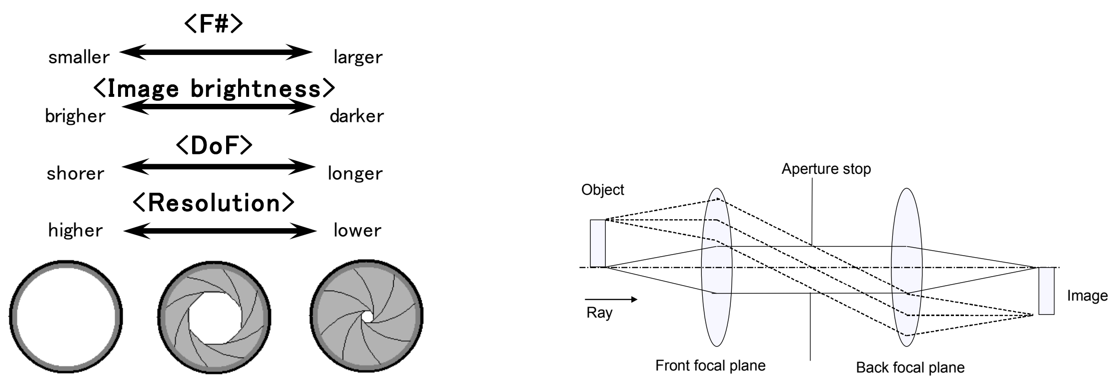
(a) Sharp-cutting filter　　(b) ND filter　　(c) Band-pass filter

Figure.4.2 Spectrum of band-pass filter(for 500nm)

(Image by Asahi-Spectra Co. LTD)[4]

(4) Aperture stop

Aperture stop is used in optical systems in order to change system F# to limit light amount to control the brightness of the images, DoF and resolution. Aperture stop is shown in Figure.4.3. Aperture stop is placed to limit amount of light most effectively.



Aperture stop (Image by Wikipedia) [3]　　Aperture stop position

Figure4.3 Aperture stop

(5) Adjustments and mounts

We need to consider adjusting optical components with precision. It is necessary to balance precision and cost. There are various kinds of kinematic mounts. It is preferable to decide it in consideration of the method of the mount and the processing cost.

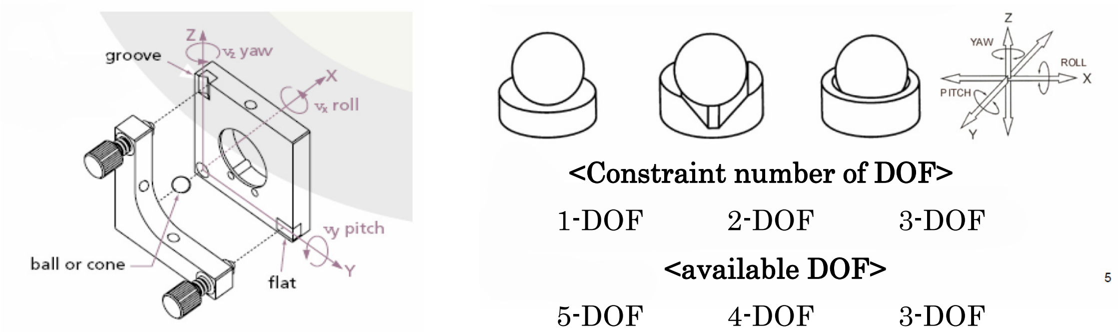
Figure.4.4 shows kinematic mirror holders. Kinematic mounts are often used for adjustment of element tilt. These are used for adjustment of mirror itself, but it is difficult for small lens system like a camera. Therefore it is desirable to loosen tilt error.

Figure.5.2.(a) shows the structure of kinematic mount for 2-axis tilt. The ball constrains the motion of the optical element. Figure.5.2.(b) shows the ball constraints. These provide translation constraint, XYZ motion, but rotational motion is free. Kinematic mounts realize tilt or other necessary motion with these constraint structures.

(a)2 axis tilt　　　　　　　(b)tilt and rotate

Figure.4.4 Kinematic holder

(Image by SIGMA KOKI CO. LTD)[6]



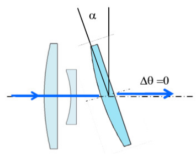
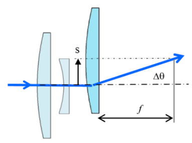
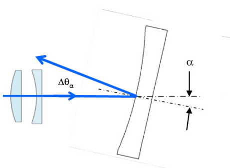
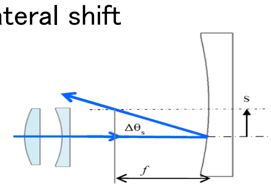
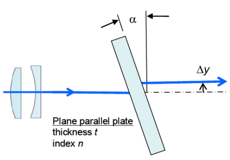
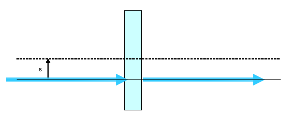
(a) Structure of kinematic mounts　　　　(b) Constraint with ball

Figure.4.5 Principle of kinematic mount[1]

5. Line of sight (LOS)

In design of optical system, lateral shift or angular deviation of LOS correspond to the image motion. It is necessary to minimize the image motion and optimize element position error. We need to think of 6 factor of element motion, which is shown in Table.5.1.

Table.5.1. System LOS change with optical element motion

	Motion Type	LOS angle	Image shift
Lens motion	(1)Tilt 	$\Delta\theta \approx 0$	$\Delta y \approx 0$
	(2)Lateral shift 	$\Delta\theta \approx \frac{s}{f}$	$\Delta y \approx \Delta\theta \cdot d$ (d is distance between image plane and back principle point)
Mirror motion	(3)Tilt 	$\Delta\theta = 2\alpha$	$\Delta y \approx \Delta\theta \cdot d$ (d is distance between image plane and back principle point)
	(4)Lateral shift 	$\Delta\theta \approx \frac{s}{f}$	$\Delta y \approx \Delta\theta \cdot d$ (d is distance between image plane and back principle point)
Filter motion	(5)Tilt 	$\Delta\theta \approx 0$	$\Delta y \approx \frac{\alpha t(n-1)}{n}$
	(6)Lateral shift 	$\Delta\theta \approx 0$ (no effect)	$\Delta y \approx 0$ (no effect)

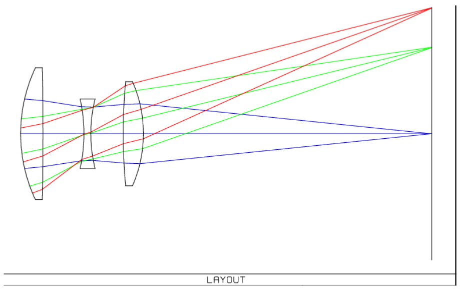
6． Wavefront aberration

At first, we design optical system ignoring elements surface error. In practice, there are defects or distortion on the surfaces of optical elements, which effect to wavefront error. Wavefront error cause degradation of optical resolution.[1]

Wavefront error is important in high-resolution system, but it is not so important if we treat low resolution optics. We need to decide quality of surface error according to resolution and cost. We need to do following three tolerance analysis. The total wavefront error is given by RSS (root sum square) of each element effect.

(1)Assembly torrelance
(2)Lenses quality tolerance
(3)Thermal changes

Table.6.1. is example of tolerance analysis for lens qualities. Analyzed system is shown in Figure.6.1. This system has 3 lenses. (so this has 6 surfaces)
(see. Report of OPTI521, Fall2009, Homework4) [1]



L1: 34 mm focal length
L2: -17 mm focal length
L3: 24 mm focal length

Figure.6.1. Analyzed optical system.

Table.6.1. Tolerance analysis of optical system

Items	Sensitivity	Sens. Units	Symbol	Error	Units	WE
Lens1 Surface1 Radius	0.007929	waves/mm	⊿R	1	mm	0.008
Lens2 Surface2 Radius	0.0006	waves/mm	⊿R	2	mm	0.001
Lens2 Surface1 Radius	0.0104	waves/mm	⊿R	1	mm	0.01
Lens2 Surface2 Radius	0.00185	waves/mm	⊿R	2	mm	0.004
Lens 1 Thickness	0.0551	waves/mm	⊿T	0.1	mm	0.006
Lens2 Thickness	0.0013	waves/mm	⊿T	2	mm	0.003
Lens1 Wedge	0.0619	waves/deg	α	0.1	deg	0.006
Lens2 Wedge	0.0972	waves/deg	α	0.1	deg	0.010
Lens1 Index Error	0.3811	waves/index	⊿n	1.00E-05	index	0.000004
Lens2 Index Error	0.4239	waves/index	⊿n	1.00E-05	index	0.000004
Surface Irregularity Lens1 Surface1	0.62296	waves/rms waves irregularity	⊿S	0.025	rms waves	0.016
Surface Irregularity Lens1 Surface2	0.62296	waves/rms waves irregularity	⊿S	0.025	rms waves	0.016
Surface Irregularity Lens2 Surface1	0.62296	waves/rms waves irregularity	⊿S	0.025	rms waves	0.016
Surface Irregularity Lens2 Surface2	0.62296	waves/rms waves irregularity	⊿S	0.025	rms waves	0.016
Lens 1 homogeoneity	0.007901	waves/rms ppm		1.25		0.010
Lens 2 homogeoneity	0.006321	waves/rms ppm		1.25		0.008
				RSS		**0.039**

We can calculate the sensitivity with optical coding program like ZEMAX or CODE-V. We have to consider the sensitivities and contributions as well as costs.

The element whose sensitivity is low can be adjusted loosely, and the factor whose sensitivity is high has to be adjusted strictly. We have to think of difficulty of machining, fabricating, or adjustment.

Tilt adjustment is generally more difficult than lateral adjustment, so contribution of tilt error is often decided larger than that of lateral error. But we always have to think of each system, so that is not always true.

7． Other effects

We need to consider thermal effects, deformation by fixing force, vibration of system or environment, adhesives used for fixing optical components. We also have to think of surface treatment of mechanical parts.

8． Conclusion

In this report, how to define or calculate these specifications, and the basic mechanisms or functions of optical elements are described.

When we design opto-mechanical systems, we should define or calculate followings,

(1) Specification of optical system
(2) What optical element to use
(3) Line of sight, the geometic features
(4) Wavefront aberration
(5) Optimize the effects of other deformation

９． Bibliography

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