# Chapter 3

⬀⬀⬀**GEOMETRIC MODEL OF SCHEIMPFLUG IMAGING**

We would like to investigate the capabilities and limitations of Scheimpflug imaging for extending the imaging volume of iris-image acquisition for biometrics.

Imaging systems primarily consists of a lens, a light sensitive surface called the sensor, and a surface in sharp focus called the object. The object and its image formed by the lens are called *conjugates*. In this work, we restrict the object and image surfaces to planes. Further, we define the plane containing the sensor as the *image plane*, the object surface (in focus) as the *object plane*, and a plane representing the lens as the *lens plane*. Amongst the several possible planes that pass through a lens, we cherry-pick a plane that provides some advantage in our model to be the lens plane.

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| **Figure 3.1** Scheimpflug camera movements. Insets (a), (b), (c), and (d) depict few key camera movements—lens and sensor plane tilts about a horizontal axis—amongst several possible, in a Sinar P3 camera. Labels indicate the lens (1), the lens standard (2), bellows (3), sensor standard (4), and the sensor (5). The cyan lines on the two standards accentuates the orientations. Inset (e) is a superimposed sequence of images of the camera with the two standards in a multitude of orientations. The physical locations of the two pivots emerge at the intersection of the superimposed cyan lines. |

In the *fronto-parallel* configuration used in common camera design, the lens and the sensor planes are parallel to each other and perpendicular to the optical axis. In such designs, the physics of optical imaging ("Gaussian Imaging equation") dictates that the object plane is also parallel to the lens and image planes. In contrast, the lens- and image- planes in a Scheimpflug camera are free to swivel about their pivots (as shown in Figure 3.1) resulting in a corresponding swivel of the object plane. We would like to exploit this feature—the freedom to arbitrarily orient the object plane—of Scheimpflug configuration to improve the depth of field of the iris acquisition devices.

Scheimpflug cameras provide the greatest flexibility for image composition; however, that flexibility is traded for complexity. Accurate modeling of Scheimpflug imaging is quite involved, and its art of operation is often left to experts who frequently employ approximate methods. While these cameras have been used in few scientific imaging applications, but the vast majority of them contemporarily are used for landscape and studio photography.

Existing models of Scheimpflug camera commonly employ overtly simple models that work quite well for documentary photography but are often restrictive and inaccurate for scientific purpose. A rich description of such cameras requires the development of a more general model. We aim to develop, in this chapter, a model for Scheimpflug imaging using the axioms of *geometric optics* (*ray optics*).

Ray optics does not provide a complete picture of imaging; yet, the definitions and postulates therein provide useful tools for the analysis and synthesis of optical systems.

Assumptions are crucial and necessary for modeling that enable its expediency and limits its applicability. For the model described herein, we have assumed paraxial imaging, rotational symmetry and aberration-free optics in order to make the problem tractable. Additionally, justified by environment in which …., we have assumed the refractive index of the lens elements and the interstitial medium to be isotropic (uniform along all directions) and homogeneous (uniform at all positions); this assumption imposes rectilinear propagation of light. Further, we have assumed the lens is surrounded by air of refractive index one. Consequently, the front and back focal lengths are equivalent, and the two nodal points coincide with the corresponding principal points.

TODO: Review what is out there. Type of models that are there, their limitations. Also, comment on the existing process of “focus-transfer” why that is erroneous. Point out, without explicitly stating, that this method has several advantages (and explicitly point out the advantages), the new insights that it provides and not a re-engineering of existing knowledge just for the sake of being different.

TO DO: State the novelty of this approach, and why needed to develop this model. Is there any relation to eikonal equations?

TODO: Preview of what is coming in the following sections.

### 3.1 Introduction

Optical imaging systems consist of several groups of elements; those elements endowed with optical power bends rays of light. The tiniest orifice in the system is called the *system aperture* or *stop*. Its interaction with the elements in the system gives rise to the pupils.

*Pupils* are the sine qua non of optical systems. They are indispensable in the design and specification of all optical systems, in both domains of *ray* and *wave optics*. The *entrance pupil* () is the “image” of the stop seen through the elements preceding it is. The *exit pupil* () is the “image” of the stop seen through the elements following it is. That is, the pupils are the images of the stop produced by the elements on either side of it. The region preceding the entrance pupil, which includes the objects and light sources, is called the object space; and the region following the exit pupil, which includes the image plane, is called the image space. The size and position of the stop (and hence the pupils) affect image resolution, aberration, brightness, and geometry.

Rotationally symmetric lenses have an axis of symmetry—the optical axis. A ray coincident with the optical axis traverses undeviated through the lens. Planes passing through the axis of such lenses are the meridional planes. Rays restricted to the meridional planes are *meridional rays*. Patterns formed by the meridional rays on either side of the optical axis are mirror-reversed, exhibiting bilateral symmetry. Figure 3.2 shows two types of meridional rays, traced in Zemax, that are fundamental to geometric analysis. The *marginal ray* (MR) originates from the axial object position and skirts the edges of the aperture and pupils (virtually); the *chief ray* (CR) starts at an off-axis object point and pierces the centers of the aperture and pupils[[1]](#footnote-1) (virtually). This pair of rays determines the location and size of the pupils, the position of the image, and the magnification. Furthermore, the bundle of chief rays from the object space converge at the center of the entrance pupil—thus *homocentric*—forming the vertex of the object-space perspective cone; in the image space, the bundle of chief rays diverge from the center of the exit pupil producing the vertex of the image-space perspective cone.

Imagine a film projector working backwards. Imagine the stream of light rays flowing from the illuminated portion of the scene towards a small circular hole in the projector. This pencil of rays forms a conical volume of light—the perspective cone—with its vertex at the hole and its base towards the scene. The “illuminated portion” is the angular extent of the scene visible in the image, confined by the circumferential chief rays. These extreme chief rays determine the opening angle of the cone. The “small hole” represents the entrance pupil of a camera or the pupil at the center of the iris in an eye. In the image space (behind the hole), the ray-pencil form another cone with the vertex at the center of the exit pupil. This image-space perspective cone projects the light from the scene onto the film surface or the retina in the eye. This process of image formation, known as the *central projection*, is fundamental to all imaging systems—inanimate and animate—including the camera and the eye. While the opening angle of the object-space perspective cone determines the field-of-view, its counterpart in the image space determines the angular dimension of the image. The ratio of the pupil sizes (pupil magnification) determines the relationship between the image and object-space opening angles of the two perspective cones.

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| **Figure 3.2** Fundamental rays (contained within the meridional plane) and pupils in a Double Gauss lens for an object at infinity. The chief rays—close to the optical axis (0°, ±5° in the object space at entrance pupil)—appear to converge at the center of entrance pupil and diverge from the center of exit pupil. The marginal ray, which is parallel to the optical axis since the object is at infinity, appear to skirt the edges of the two pupils. The red circles specify the vertices of the perspective cones (centers of the pupils). The rays were traced in Zemax. |

### 3.2 Notation (this section is currently a placeholder for the notation, skip reading this for now. I will write it appropriately after completion of the major math)

* Right-handed coordinate system with the +z along the direction of travel of light, (left to right in the plane of drawing)
* In general, non-primed quantities are used to indicate input or object space (e.g.) and primed quantities are used to indicate output or image space (e.g.).
* Unit vectors are represented using a hat (), with the exception of the direction cosine vectors (e.g. although the norm of the direction cosine vectors are unity.
* A left superscript indicates the frame of reference. For example, indicates that the variable is w.r.t. the world coordinate frame. If no reference is explicitly stated it implies that the variable is w.r.t. the world coordinate frame (or the camera coordinate frame if the camera coordinate frame and the world coordinate frame are the same.
* A subscript is used to associate a variable with a particular xxx like entrance pupil position (), image plane (), for example is used to represent the 3D rotation matrix applied to the entrance pupil plane in the camera frame. The same notation is also used to indicate a transformed variable, for example is used to represent under the rotational transformation by in the camera coordinate frame. As also mentioned earlier, if the camera coordinate frame is the same as the world coordinate frame, then the notation shall be used.
* represents the pose of frame w.r.t. frame TO DO: mention how a point in one frame is represented in another frame.
* The one-based indexing of matrices and vectors. Also a matrix is also represented as where are the columns of .
* Describe what I mean by lens plane.
* Overloading of the term “direction cosine(s)” and “direction cosine vector”. It should be clear from the context
* Point out notation for angles , , ,

### 3.3 Relation between pupil magnification and chief ray angle

The *pupil magnification* is defined as the ratio of the paraxial exit-pupil diameter to the entrance-pupil diameter [refref].

Figure 3.3 illustrates the meridional and sagittal planes associated with an arbitrarily located object of height above the optical axis and its image of height in a typical optical system. The figure also shows the chief ray from the object’s edge further from the optical axis, the marginal ray from the axial point in the object, and the two pupils contained in the meridional plane. The schematic, although simple, is quite general as a (meridional) plane always exist for a given object point irrespective of its position in the three-dimensional space, if the lens is rotationally symmetric.

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| **Figure 3.3** Schematic of chief and marginal rays. The ratio of the tangents of the chief ray angles in the object space to the image space yields the pupil magnification. |

Let the angles between the chief ray and the optical axis (called the *ray-angle*) in the object- and image-space be and respectively. Also, let the angles produced by the marginal ray with the optical axis in the object- and image-space be and respectively. Then, we can obtain the relation between the chief ray ray-angles— and —and the pupil magnification as follows:

From the Figure 3.3,

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Eliminating and after dividing by, we have

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A common observation in imaging is that we can increase the transverse magnification () by increasing the lens-to-image-plane distance while correspondingly decreasing the lens-to-object-plane distance in order to maintain focus on the object. However, increasing (decreasing) the image plane distance proportionally decreases (increases) the marginal ray angle (see Figure 3.3). Consequently, the angular magnification () decreases with increase in lens-to-image-plane distance. Therefore, a large transverse magnification is associated with a correspondingly small angular magnification. This result follows from a more general theory called the *Lagrange invariant* [ref] property of the two rays (the chief ray and the marginal ray) when applied between conjugate locations. As per the invariant property, the product of the transverse magnification and the angular magnification equals to one, i.e., or. Cancelling the corresponding terms in Eq. (3.2) yields the relationship between the pupil magnification and the object- and image-space chief ray angles:

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The above relation (Eq. (3.3)) has been previously derived in [ref] using a different formulation.

For a given optical system, the pupil magnification is constant. This constancy of the ratio of the tangents of the chief ray angles for varying object (and image) heights is a necessary and sufficient condition for distortion-free imaging known as the *Airy’s Tangent-Condition* [ref]. Eq. (3.3) also suggests that when the perspective cones in the object- and image-space are symmetric. In the following section, we will use Eq. (3.3) to derive the relationship between the direction cosines of the object-space (input) chief rays and direction cosines of the image-space (output) chief rays.

### 3.4 Transfer of chief ray’s direction cosines between the pupils

The direction cosines, a unit vector of cardinality three, specify the direction of a ray. Its elements are the cosines of the angles the ray makes with the three coordinate axes. In other words, the elements of the direction cosine vector are the projections of the unit vector in the direction of the ray on the x-, y-, and z-axes. Given the direction cosine of the chief ray in the object space, we would like to know the direction cosine of the corresponding ray in the image space. Furthermore, what is the relation between the input and output chief ray’s direction cosines if the lens is swiveled about a pivot point along the optical axis?

We begin by solving a specific problem of the *transfer* of the direction cosines between the pupils in which the optical axis coincides with the z-axis of the camera frame, as show in Figure 3.4. Subsequently, we will deduce the general *transfer* expression in which the optical axis is free to swivel about the origin of. Let be the direction cosine of the chief ray from a world point to the center of the entrance pupil, and let be the corresponding direction cosine of the chief ray from the exit pupil. The parameters , ,and are specified with respect to frame .

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| **Figure 3.4** Specific problem—optical axis coincides with reference frame’s z-axis. If and are the angles of the CR with the OA in the object- and image-space respectively, then and. |

If and are the zenith and azimuthal angles of the chief ray in the object space, and and the corresponding angles in the image space, then the direction cosines, in , are:

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Since the optical axis is aligned with the z-axis, and. Substituting the expressions for from Eq. (3.4) into Eq. (3.3) we obtain:

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Further, since the input and out chief rays are confined to the same meridional plane [ref], , yielding and in terms of and , the ratios of to , and :

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From (3.3) we have

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which after simplification yields in terms of the pupil magnification and input

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Combining Eqs. (3.6) and (3.8), we obtain the expression for output direction cosine of the chief ray in terms of the input direction cosines and the pupil magnification as:

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which we can write compactly as:

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Our objective is to derive the expression for the transfer of the chief ray’s direction cosines from entrance pupil to exit pupil for arbitrary orientation of the optical axis as shown in Figure 3.5. Although a formal derivation is provided in [Appendix], we can readily infer the general *transfer* expression from Eq. (3.10) as follows:

Suppose we swivel the optical axis about the origin of the camera frame. This rotation can be described by the matrix. As before, we designate the ray from the object-point to the (new position of the) center of the entrance pupil as the chief ray. Let us also suppose that we have another coordinate frame,, sharing its origin with and its z-axis coincident with the optical axis. If be the direction cosine of the chief ray from the object-point in the frame , then the direction cosine in the frame is and the third element of the direction cosine is , where is the third column of . Representing, the direction cosine of the chief ray emerging from the exit pupil is obtained by substituting for and for in Eq. (3.10):

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The above expression represents the output direction cosine in the coordinate frame In order to transform the output direction cosine from the coordinate frame to the camera frame we need to multiply the direction cosine vector by to obtain:

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| **Figure 3.5** Configuration of the general problem—optical axis (OA) pivots freely about the origin of. |

The positive or negative sign of the direction cosine determines the forward or backward direction of light-travel along a rectilinear path. Under the assumptions of isotropy and homogeneity, the only condition under which a ray of light emerges in an antipodal path from an interface is if it encounters a mirror surface *normally*. This condition does not arise within the context of our problem. Therefore, without any loss of generality, we can drop the negative sign in Eq. (3.11); accordingly, the output direction cosines assume the sign of the corresponding input direction cosines. Therefore, the general expression for the direction cosines of the chief ray in the image space is obtained as:

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where.

Note that Eq. (3.12) only describes the output chief ray’s direction cosines—a free vector. The output chief ray is obtained from the knowledge of the direction cosine and the location of the exit pupil in the appropriate reference frame.

Although it is not obvious from the expression (3.12), we expect to have unit magnitude. We have provided a proof in [Appendix] that shows the (magnitude) of is indeed equal to one, and is the normalizing term.

We can draw the following inferences about from the Eq. (3.12):

1. If the pupil magnification, , then , which implies that the opening angles of the image- and object-space perspective cones are equal, irrespective of the orientation of the optical axis. Then, the lens is symmetric about a plane perpendicular to the optical axis (in addition to the symmetry about the optical axis). Such symmetric lenses are can be reversed without affecting system properties [ref].
2. If we let, such that, then we can write , where is the scalar normalization term. Furthermore, as is a diagonal matrix, and is orthonormal, can immediately recognize the form as the Eigen value decomposition of the symmetric matrix, with —the columns of —as the eigenvectors and the corresponding eigenvalues. As is a diagonal matrix,

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In Eq. (3.13) the terms are the projections of the input direction cosine along the eigenvectors. Also,, which is the third column of the rotation matrix , is the direction of the optical axis. The effect of the transformation is a *shearing* of the input direction cosine along the optical axis.

### 3.5 Image formation for arbitrary orientation of the lens and image plane

Geometric imaging is a mapping (*bijective* in projective space) between points in the three-dimensional world space to corresponding points on a mathematical surface that we call the *image*. Here we aim to study the nature of this mapping on a planar surface—the image plane—for arbitrary orientations of either the lens and image planes. To that effect, we will use the knowledge of the transfer of direction cosines of the chief ray derived previously.

An extended object emanates a multitude of chief-rays that reach the image space through the pupils and the stop. The locus of points formed by the intersection of these rays with the image plane constitutes the *projection* of the object in the image plane [ref]. Further, we identify the projection of the world-point as an “image” if the pencil of rays (including the chief-ray) from the world-point, filling the pupils and stop, geometrically converge at a single point in the image space.

For simplicity, we assume that the lens is unencumbered by radial distortions and optical aberrations. Figure 3.6 represents a schematic of the problem in which we have introduced an image plane whose orientation is described by the unit surface normal. Two local frames are also introduced: the frame is attached to the optical axis with its origin at entrance pupil (), and the frame attached to the image plane with its origin at the image plane pivot. The image plane is free to swivel (tilt or swing about its local x-axis or y-axis respectively) about the image plane pivot.

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| **Figure 3.6** Schematic of geometric image formation. is the *central* *projection* of the world point on image plane. The optical axis and image plane are free to swivel about the origins of coordinate frames and respectively. |

Let the exit pupil () be located units from the pivot point along the optical axis. Following the rotation of the optical axis, by applying the matrix, the position of the exit pupil in is given as.

We can represent the chief ray emerging from the exit pupil with direction cosine by the parametric equation:

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where represent points along the output chief ray in. The first term on the R.H.S. of Eq. (3.14) is the initial position of the ray (at the center of) and is a real number that determines the length of the ray.

The equation of the image plane in Hessian normal form is

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where is the unit normal to the image plane, is the perpendicular distance from the origin of frame to the plane, and is an arbitrary point on the image plane.

We obtain the expression for (in Eq. (3.14)) for which the ray intersects the image plane by equating to, multiplying Eq. (3.14) by, and rearranging the terms:

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Substituting Eq. (3.16) into Eq. (3.14) we get

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Now we proceed to find the expression for in terms of the known parameters. The origin of the image plane’s local reference frame,, is located at the intersection of the z-axis of camera frame with the image plane (see Figure 3.7). Given the point , we can describe the orientation of the image plane using the surface normal, which is obtained by applying to the unit vector :

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The equation of the image plane is

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Since is a point on the plane,

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| **Figure 3.7** Schematic of the image plane. The image plane having surface normal is located at units from the origin of camera frame along the z-axis that intersects the plane at . is the perpendicular distance from the origin to the plane. The local image coordinate frame with its origin at the intersection of the image plane and z-axis of the camera frame is represented by . |

Using the above result in Eq. (3.17) yields the expression for the point of intersection of the chief ray with the image plane in terms of the input direction cosines as

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Similar to the exit pupil, let the entrance pupil be located at a distance from the pivot point along the optical axis in the camera frame. Then, the location of the entrance pupil in is.

The direction cosines and the world point are related as

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which can be written compactly as:

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Substituting Eq. (3.22) into Eq. (3.20), a general relation between the world point and its corresponding image point is obtained as:

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Eq. (3.23) represents the image point in the camera frame. Once an image is formed, we specify positions and dimensions within the it independent of the position and orientation of the sensor and lenses (e.g. in terms of pixels in a digital image). We can transform the image coordinates in the camera frame to the image frame by observing that the origin of is displaced from by , and the standard basis vectors of are rotated by . Consequently, a point in relative to may be expressed as:

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Therefore, we can write the expression for the image point coordinates with respect to the image plane’s reference frame as

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Substituting from Eq. (3.23) into Eq. (3.25) we obtain the expression of the 2D image point in the image frame as

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Where,

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|  | 3D Cartesian coordinates (in physical units) of the world point in camera frame . In the adopted coordinate convention, the z-component of is negative. |
|  | 2D Cartesian coordinates (in physical units) of the image point in the image frame . Note that Eq. (3.26) produces a 3x1 vector with the third element identically equal to zero. |
|  | Equal to , where is the pupil magnification. |
|  | Location of the entrance pupil from the pivot (origin of ) along the optical axis. This scalar quantity physical units, usually in millimeters. |
|  | Location of the exit pupil from the pivot (origin of ) along the optical axis. |
|  | Location of the image plane from the pivot (origin of ) along the z-axis of . |
|  | Rotation matrix used to describe the orientation of the lens plane. |
|  | The third column of . |
|  | Rotation matrix used to describe the orientation of the image plane. |
|  | The image plane normal. denotes the z-component of the normal. |

We derived the Eq. (3.26), which relates a 3D object point to its projection in the 2D image plane of a Scheimpflug camera, analytically. Now we show that the relationship is accurate by comparing the numerically computed values of image points (intersection of chief ray with the image plane) using Eq. (3.26) with corresponding image points obtained by tracing chief rays from a grid of points in an object plane. Figure 3.8 is a layout plot of an optical system created in Zemax, showing the object plane; an ideal lens made from two paraxial surfaces and pivoted about a point away from the entrance pupil (); and an image plane pivoted about the image plane pivot along the z-axis. Both the lens and image planes are arbitrarily rotated (about their local frames) with respect to both x- and y-axis. The orientations of both the planes are represented using intrinsic rotations (elemental rotations first about the x-axis and then about the new y-axis) matrices. and represent the angles of rotation of the lens plane about the x- and y- axes while and represent the angles of rotation of the image plane about the x- and y- axes. The set of object points, the numerically computed image points, the Zemax ray traced image points, and the absolute difference between the numerically computed and ray traced image points are tabulated in Table 3.1. It shows that the difference between the numerically computed and ray traced values of the image points are in the order of XXX. This comparison demonstrates that the algebraic expression that expresses the geometric relation between a 3D world point and its image point in the absence of optical aberrations is accurate.

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| **Figure 3.8** Ray tracing for verifying Eq. (3.26). Chief rays traced from a grid of points in the object plane through an ideal lens tilted about a point away from the entrance pupil along the optical axis to the tilted image plane. |

**Table 3.1** Comparison of numerically computed image points with ray-traced image points for the optical system shown in Figure 3.8.

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| World point | Computed image point | Ray-traced image point | Absolute difference |
| (0.0, 0.0, -509.0) | (-0.3108, -0.6291, 0.0) | (-0.3108, -0.6291, 0.0) | (1.8e-09, 3.1e-09, 7.5e-15) |
| (10.0, -10.0, -509.0) | (-0.8003, -0.0863, 0.0) | (-0.8003, -0.0863, 0.0) | (2.1e-09, 2.7e-09, 3.0e-15) |
| (-50.0, 50.0, -509.0) | (2.1291, -3.3352, 0.0) | (2.1291, -3.3352, 0.0) | (1.2e-09, 3.2e-09, 2.9e-15) |
| (70.71, 70.71, -509.0) | (-4.2013, -5.0221, 0.0) | (-4.2013, -5.0221, 0.0) | (2.6e-09, 5.1e-09, 4.7e-15) |
| (100.0, 0.0, -509.0) | (-5.5251, -1.0101, 0.0) | (-5.5251, -1.0101, 0.0) | (1.3e-09, 8.4e-09, 3.1e-15) |
| (0.0, 100.0, -509.0) | (-0.6031, -6.4387, 0.0) | (-0.6031, -6.4387, 0.0) | (2.2e-09, 4.0e-09, 2.2e-16) |
| (100.0, 100.0, -509.0) | (-5.8238, -6.8542, 0.0) | (-5.8238, -6.8542, 0.0) | (5.6e-10, 2.5e-10, 2.2e-15) |

Following the verification of the analytic expression, we use it to briefly study the effect of lens and image plane rotations on the properties of the geometric image. Figures 3.9 – 3.12 show the nature of geometric distortions in the image of a grid of points from two object planes for varying image plane rotations, lens plane rotations, pupil magnifications, and offset of the lens’ pivot from the entrance pupil position (ENPP). In all these figures, the basic setup is similar to that shown in Figure 3.8 except that the object space consists of two planes at distances of 500 *mm* and 1000 *mm* from the entrance pupil. The dimensions of both the object planes is 100 *mm* by 100 *mm*. The z-axis of the camera frame passes through the center of both planes. The image points, shows by the dots in Figures 3.9 – 3.12 are the intersections of the image plane and the chief-rays emanating from a 7x7 square grid in the object planes. The lighter shaded orange dots represent the group of image points from the object plane that is closer to the lens (500 *mm*) in frontoparallel configuration (i.e. when the object planes are parallel to lens and image planes). The lighter shaded blue dots represent the image points from the object plane further to the lens (1000 *mm*) in the frontoparallel configuration. Note that since the z-axis of the camera frame passes through the centers of both the planes, their projections onto a physical sensor would have overlapped; however, the image points from the near and far object planes in the plots were displaced horizontally by 5 *mm* on either side of the center for the sake of visual clarity. The darker shaded dots of either colors show the image points subsequent to the image-, or lens-, or both plane’s rotations. Rotation of either planes induces a geometric distortion of the image field in which the image points shifts by different amounts. These translations are shown by the gray arrows between the original and shifted positions (drawn if the magnitude of the shift is greater than a certain threshold). The black level of the arrows indicates the normalized magnitude of translation—darker indicates larger translation. The translation magnitudes are normalized within each group of image points for visual clarity. Note that in all cases shown here, the image points are not determined by best focus criterion, but rather by the location of intersection of the chief ray with the image plane. However, this definition of the *image* adopted for the current discussion does not limit the study of geometric properties, such as the kind of affine transformations induced by the rotations of the sensor and lens planes.

Here are some key observations:

Only image plane rotation ():

1. The image points undergo a geometric distortion, called perspective distortion, that is field dependent and asymmetrical. The field dependence and asymmetry can be observed by the length of the arrows between the initial and shifted positions of the image points across the image field in Figure 3.9 (a). The perspective distortion is a manifestation of the field dependent magnification because the image plane ceases to be frontoparallel with the object planes.
2. The amount of perspective distortion depends on the pupil magnification—larger for optical systems with pupil magnification less than one and smaller for optical systems for pupil magnification greater than one.
3. Since the location of neither the entrance pupil nor the exit pupil remain fixed, the on-axis image point continues to remain on-axis subsequent to the rotations. Furthermore, if the image plane is rotated only about one axis, then image points along the line in the direction of that axis and through the on-axis image point continue to remain in the same position following the rotation of the image plane.
4. Since the perspective distortion is also dependent on magnification, the amount of distortion is inversely proportional to the distance of the object plane from the lens.
5. Although, the on-axis image point (or image points through a line if the rotation is just about a single axis) does not undergo any shift following image plane rotation, the *centroid* of a set of image points inevitably shifts due to the translation in positions of the off-axis points. Furthermore, the amount of shift of the centroid of a set of image points is dependent on the object-to-lens distance.

Only lens plane rotation ():

1. The dominant effect of rotating the lens about a point along the optical axis is, in general, a *non-uniform shift* of the image field. The term *non-uniform* means that all points from a group of points in the image field do not shift by the same amount. This can be observed by the length of the arrows in Figure 3.10.
2. Due to the shift of the image field, both the initially on-axis image point and the centroid of a group of image points, shifts following the rotation of the lens as shown in Figure 3.10 and Figure 3.12 (c).
3. In general, the amount by which the centroid of a group of image points shifts across the image plane depends upon the pupil magnification and the object distance. As shown in Figure 3.10, the shift is small if pupil magnification is greater than one and large if it is less than one.

Figure 3.11 shows few cases in which both the lens and image planes are rotated (). The group of image points undergo both shift across the image field (due to lens rotation) and perspective distortion (due to image plane rotation). Both the initial image center and the centroid of a group of image points undergoes translation.

We have heretofore qualitatively examined the properties of the geometric image in a general Scheimpflug imaging configuration in which the sensor plane is rotated about a point located along the z-axis of the camera frame, and the lens is rotated about a point that is different from the entrance pupil position (ENPP). Since the center of the entrance pupil is the center of projection (point of convergence of all the chief rays from object space) in the object side, rotating the lens about a pivot away from the entrance pupil also rotates of the entrance pupil center about the pivot point. Therefore, the rotation of the lens about a point away from the center of the entrance pupil position induces a translation of the center of perspective along x-, y- and z- axis of the Euclidian space.

* Case (qualitative) of rotating about ENPP
* Case (qualitative) of using pupil magnification equal to one.

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| **Figure 3.9** Geometric image under image plane rotation for varying pupil magnifications. (a) , (b) , (c) . The image plane in each case is tilted about the x-axis by 20°. |
|  |
| **Figure 3.10** Geometric image under lens rotation for varying pupil magnifications. (a) , (b) , (c) . The lens is rotated about the x-axis by 5° about a point -5 *mm* away from the ENPP along the optical axis. |
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| **Figure 3.11** Points of intersection of chief rays with image plane tilted by 20° & lens plane tilted by 5° about the x-axis. The 200 sq. mm object grids were positioned 1000 mm (left) and 500 mm (right) mm away from the ENPP. (a) , (b) , (c) . |
|  |
| **Figure 3.12** Centroid shift. (a) The shift is independent of object distance () if and only the lens is rotated about the ENPP, (b) the shift is dependent on if the image plane is rotated even if and the lens is rotated about the ENPP, and (c) the shift depends on if the lens pivot is away from the ENPP. |

### 3.6 Object, lens and image plane relationships in Scheimpflug imaging

In this section, we will derive a *general expression* that relates the object, lens and image planes. We will further show that this general expression yields relationships that are more specific to various types of Scheimpflug configurations. In order to keep the problem tractable, we will impose the constraint that three pivots lie along the z-axis of the camera frame, and the origin of is co-located with optical axis’ pivot. We also bound the angle of rotations of object, lens, and image planes between and about both x- and y- axes (in-plane rotations or rotations about the z-axis is irrelevant for our purpose). Provided we make no distinction between the faces (front or back) of the planes, this bound on the angles of rotations is not limiting in any way since we can uniquely describe all possible planer orientations in three dimensions. On the other hand, this bound warrants non-negative values for the z-component of the plane normal. As we will see later, this warranty permits us to unambiguously estimate the unknown plane normal.

We begin by deriving an expression for the chief ray joining an arbitrary point in the object plane to a point in the image plane. In order for to be the geometric image of , the chief ray conjoining the conjugate points must satisfy the Gaussian imaging equation. This constraint allows us to uniquely determine the position (of the image plane along the z-axis of) and orientation of the three planes in Scheimpflug configuration. The setup is shown in Figure 3.13.

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| **Figure 3.13** Schematic of Scheimpflug imaging. The figure shows the object plane, optical axis and image plane pivoted about points along the z-axis of the camera frame. The local object plane and image plane coordinates ( and) are centered at the object- and image- plane pivots. |

The object plane is located at a distance of from the origin of camera frame, along the z-axis. Pivoted about the point in the camera frame, it is completely described by the object plane pivot and the plane normal,. We describe the normal itself as the product of the rotation matrix and ().

That is, the equation of the object plane normal is

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We can obtain the perpendicular distance to the object plane from the origin as

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Then, the equation of the object plane in Hessian Normal form is

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where is any point on the object plane.

Similar to the object plane normal, we describe the image plane normal as

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where is the rotation matrix applied to the image plane at the image plane pivot point .

Repeating the steps used to derive the object plane equation, the equation for the image plane is

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where is any point on the image plane.

Suppose the entrance () and exit () pupils are located at distances and from the lens plane pivot point (origin of) respectively, along the optical axis. Also, let us describe the rotation of the optical axis by applying the matrix. Then, following the rotation, the positions of the pupils in are

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Consider the chief ray from the object-point , to the corresponding image point , passing through the center of the entrance and exit pupils. Let the direction cosines of ray in the object- and image- space be and respectively. We can describe a line along the ray originating at the entrance pupil and extending backwards towards the object plane in parametric form as

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where is any point on the line (chief ray), is the position of the entrance pupil, and the parameter determines the length of the ray.

Let the length of the ray between the object-point and the entrance pupil be. Then, in Eq. (3.34), when, which implies that

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Since is a point on the object plane, it satisfies the object plane Eq. (3.29). Substituting into Eq. (3.29) we get

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The chief ray emerges from the exit pupil, having a direction cosine vector, and intersecting the image plane at to the right (positive z direction) of the exit pupil. Therefore, the parametric equation of this chief ray is

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where is any point on the ray, is the position of the exit pupil, and is the length of the ray.

If we let the length of the chief ray in the image space be, then when in Eq. (3.37), implying

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Substituting in Eq. (3.31) we get

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Eqs. (3.36) and (3.39) are expressions for the lengths of the chief ray between points and in the object and image space respectively. In order for to be the geometric image of , the expressions must satisfy the Gaussian imaging equation.

The well-known Gaussian imaging equation () relates the focal length and the conjugate plane distances measured from the principal planes. Instead, if the distances are measured from the pupils (entrance pupil to object plane and exit pupil to image plane) in lieu of the principal planes, then a variant of the Gaussian imaging equation is used. The updated imaging equation, which incorporates the pupil magnification into the formula, is

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where and are distances along the optical axis measured from the entrance pupil to the object plane and from the exit pupil to the image plane, is the pupil magnification, and is the focal length. We have provided a derivation and a brief exposition of the above formula in [Appendix].

The most common application of Eq. (3.40) is for fronto-parallel imaging in which the conjugate planes are parallel to each other and perpendicular to the optical axis; moreover, all pairs of object-image conjugate points satisfy this relation even if the ensemble of object points and image points belong to planes on object and image spaces respectively that are *not parallel* to each other.

The ray vector of length and direction in the object space is. The projection of this ray vector on the optical axis () is. Similarly, the ray projection of the image space ray vector on the optical axis is. Substituting and in to Eq. (3.40) we have:

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Further, substituting the expressions for and (Eqs. (3.36) and (3.39)) into the above equation, we have

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The direction cosine of the chief-ray in the image space,, is related to the direction cosine of the chief-ray in the object space as (Eq. (3.12))

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Substituting, into Eq. (3.42) we have

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To simplify the above expression, let us consider as

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Therefore, we can write in Eq. (3.43) as. Similarly, we can also write as. Then, Eq. (3.43) can be written as

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We can further simplify the above equation by noting that:

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4. .

Therefore, Eq. (3.45) reduces to

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Further, following a trivial algebraic manipulation we get

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Note that in the above expressions, the third column of the rotation matrix, is the unit vector along the optical axis.

Since is a direction cosine vector with -Norm equal to one, the above equation is satisfied if the second vector,, is either perpendicular to or identically equal to zero. Let us consider the possibility of the former case. *All* chief rays—an infinitude of vectors within the object and image space perspective cones—must satisfy Eq. (3.47). Are all possible vectors perpendicular to the second vector? Since the second vector is a linear combination of (the object plane normal), (the transformed image plane normal), and (unit vector along the optical axis) whose weights are constant for a given system, we can conclude that is not perpendicular to the second vector *in general*. Therefore,

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Further, we can simplify Eq. (3.48) if we let and. Then, after factoring and out from the denominator terms, we can write Eq. (3.48) as

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This expedient simplification relies on our ability to describe the *unit* normal vectors and using only components along x- and y-axes. For example, if the object and lens plane orientations and distance are known, and we estimate the image plane distance and orientation vector () of the image plane using Eq. (3.49), then we can determine the image plane normal as

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where , , and we have dropped the negative sign from the expression for since is guaranteed to be positive as discussed under the assumptions at the beginning of this section.

Comment about why only the chief ray is sufficient to determine the image plane location and orientation, intuitively. ….

Eq. (3.49) is most general in the sense that it readily yields the various expressions for specific cases of object, lens and image plane orientations as we now demonstrate in the following set of examples.

**Example 3.1:** If the object plane is perpendicular to the optical axis and units from the origin of camera frame, what is the orientation and position of the image plane?

Assuming, the distance of the entrance pupil from the origin of, is non-zero, the object plane is located at a distance of () from the entrance pupil, where is numerically negative.

1. Since the lens is not tilted, ,
2. Since the object plane is also not tilted,
3. Let, and. Then,

Substituting the above parameters in Eq. (3.49) we have

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which yields the following relations from each row of Eq. (3.51):

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Writing and where, is the directed distance from the entrance pupil to the object plane and is the directed distance from the exit pupil the image plane, we can rewrite Eq. (3.54) as

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Further, if, then the sign of is positive, a condition that is typical in macroscopic imaging. For example, if, and, then is positive for. In a survey of 120 imaging lenses (see Appendix xxx) from a database (Zemax Zebase) of well-designed lenses, we found over 90% of all lenses to have pupil magnification greater than 0.5 and no lens having pupil magnification less than 0.2. Thus, in the common imaging scenarios, the sign of is positive.

From Eqs. (3.52) and (3.53) we see that the image plane normal is equal to. That is, the image plane is parallel to the lens and object plane and perpendicular to the optical axis if the object plane is parallel to the lens plane.

For thin lens model (,), Eq. (3.54) reduces to the Gaussian lens equation for thin lenses:

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If the distances to the object and image plane are specified from the object and image space principal planes instead of the pupils, Eq. (3.54) reduces to ()

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in which, is the distance of the object plane from the object-space principal point, and and represent the locations of the object- and image-space principal points in the camera frame . While is numerically negative, the signs of and depend on the position of the principal points with respect to the origin of.

**Example 3.2:** If the object plane, pivoted at, is tilted by an angle about the x-axis in the camera frame (Figure 3.14), what is the conjugate orientation and position of the image plane?

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| **Figure 3.14** Object and image plane tilt. In the above cross-sectional (y-z plane) view, the object plane is tilted by an angle of about the x-axis at. We would like to determine the position and orientation of the image plane that brings the object face in sharp focus. |

1. Since the lens is not tilted, ,
2. Let, and. Then,
3. Let, and. Then,

Substituting the above parameters in Eq. (3.49) we have

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As in the Example 3.1, the distance of the image plane pivot in the camera frame, obtained from the third of Eq. (3.58), is

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As in Example 1, writing and where, is the directed distance from the entrance pupil to the origin of the object plane and is the directed distance from the exit pupil to the origin of the image plane, we get

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in which is numerically negative and is positive for macroscopic imaging.

From the first and second rows of Eq. (3.58), we have

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and

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Since the object plane is rotated by about the x-axis, the rotation matrix is

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Note that if the direction of rotation of the object plane about the x-axis is from +z-axis to +y-axis (as depicted in Figure 3.14), then is numerically negative.

The object plane normal is (Eq. (3.27))

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from which, we can get by dividing by

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Substituting into Eqs. (3.61) and (3.62) we get

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Eq. (3.66) in conjunction with Eq. (3.50) suggest that, which implies that the image plane normal is confined to the y-z plane. That is, if the object plane is rotated about the x-axis, then the image plane must also be rotated about the x-axis. Further, under the common macroscopic imaging scenarios, and is numerically positive and is numerically negative. Therefore, is numerically positive implying that the sign of is determined by the sign of angle. For example, if is numerically negative, as depicted in Figure 3.9, then and hence is negative, which implies that the image plane is rotated about the x-axis in the opposite direction compared to the rotation of the object plane. The exact expression for the components of the image plane normal is obtained by substituting and into Eq. (3.50). Angle of the image plane normal with respect to the three axes is then obtained as the cosine inverses of the corresponding components of the normal vector.

Furthermore, it is a desideratum to have a more direct relationship between the rotation angles of the object and image planes. To that end, let us suppose that the required image plane tilt (rotation about the x-axis) is. If we represent the rotation matrix of the image plane as

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it yields the image plane normal as

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which produces as

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Substituting (from Eq. (3.69)) into Eq. (3.66) we obtain

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where is numerically negative, and, obtained from Eq. (3.59), is almost always positive for macroscopic imaging. Thus, the sign of (hence the direction of rotation of the image plane) is opposite to the sign of (the direction of rotation of the object plane), as we had already established before.

We can further modify the above relation if the distances are specified with respect to principal planes (Figure 3.15). Then, represents the magnification between the image and object side principal planes and, therefore, is equal to one; the ratio represents the ratio of the distances of the principal-plane-to-object plane in the object side and principal-plane-to-image plane in the image side along the z-axis, and therefore is equal to the magnification along the z-axis. Letting, and, we can rewrite Eq. (3.70) for distances measured between as

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write about

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| **Figure 3.15** Object and image plane tilt (distances measured from principal planes). In the above cross-sectional (y-z plane) view, the object plane is tilted by an angle of about the x-axis. The distances to the object and image plane pivots are specified from the respective principal planes. |

**Example 3.3:** If the object plane is swiveled about a pivot that is located at in the camera frame while the lens plane remains static, what is the orientation and position of the image plane?

**Example 3.4:** Thin lens, only lens plane tilt

**Example 3.5:** Thick lens, only lens plane tilt

# Appendix⬀

### Derivation 3.1

Later, we will apply the method of induction to yield the solution of the general *transfer* problem—in which the optical axis is free to swivel about the origin of.

Eq. (3.9) accurately represents the *transfer* for the specific problem; however, we will cast the expression in a slightly different form whose raison d'être is to enable generalization—through direct application of the result. Specifically, we can express the output chief ray as a linear combination of the input chief ray and the optical axis since the two rays and the optical axis span the same (meridional) plane. Let, the standard basis vector along z-axis of, represent the optical axis since the optical axis is coincident with the z-axis. Then,

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where and are the weights, and.

Rewriting the above equation as

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the weight is readily obtained by comparing Eqs. (3.9) and (4.2):

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Substituting the expression for into and comparing with (3.8) yields:

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We are now ready to apply the result of the specific problem to the general problem. Figure 3.4 shows the schematic of the general problem—the optical axis pivots about the origin of. Let us describe the general orientation of the optical axis by the action of the rotation matrix on. The matrix may be a composition of two or more matrices that denotes a sequence of rotations about the x-axis and/or y-axis. Then,, the unit vector representing the new orientation of the optical axis, is obtained as: or .

As the output direction cosine, the input direction cosine, and the optical axis lie on the same plane,

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Note that the input direction cosine in Eq. (4.5) is different from the corresponding in Eq. (4.1) even for the same object-point . This difference is due to the displacement of entrance pupil () following the rotation of the optical axis; in fact, the designation of a ray as the chief ray (from to) keeps altering as we keep displacing the entrance pupil. Multiplying Eq. (4.5) by:

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Letting and,

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Comparing Eqs. (4.1) and (4.7) the expressions for the weights and are obtained as:

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Where represents the projection of the direction cosine vector, **,** on the rotated optical axis. If we write the matrix where are the columns of . Then,

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and

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Therefore, since is the third element of.

Rewriting Eq. (4.7) as:

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which can be compactly written as:

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Finally, substituting and yields the general expression for the direction cosines of the chief ray in the image space in terms of the pupil magnification and direction cosines in the object space as:

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where.

### Claim 3.1 The output direction cosine, originating from exit pupil, has unit -Norm

The direction cosine in the image space, obtained by the linear transformation of the direction cosinein the object space, has unit , and is the normalization term.

*Proof*.

The expression for the direction cosine in the image space is

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where , is the column of the rotation matrix applied to the optical axis, , and is the pupil magnification.

Our objective is to prove.

For the convenience of notation within the proof, let

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where, and , the diagonal matrix with non-negative real values.

Also, let us represent the columns of as

Then, , and

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Now, since is a rotation matrix, it is orthonormal (the column of, having unit length, are orthogonal to each other). Therefore, .

Then,

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where

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where and .

As is a diagonal matrix, we can rewrite as

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Now,

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Also

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Substituting in Eq. (4.15),

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Substituting into Eq. (4.14) we have

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It follows that the scalar quantity is the normalization term. ☐

### Derivation 3.2 Gaussian imaging equation with pupil magnification

The familiar Gaussian imaging equation, , relates the directed object and image plane distances with the focal length . is the directed distance (numerically negative) between the object plane (perpendicular to the optical axis) and the principal plane () in the object space, is the directed distance (numerically positive for *real* images) between the in-focus image plane and the principal plane () in the image space. The distances being measured along the optical axis.

If the distances of the object and image planes are specified from the entrance () and exit pupil () instead of the principal planes, then the Gaussian lens formula needs to be slightly modified to incorporate the pupil magnification (). Here we derive the modified formula starting from the Gaussian lens formula. The same result was derived in [Ref] using a slightly different approach.

Figure x.x shows a schematic of the entrance and exit pupils, the object and image space principal planes, and the object and image points.

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| **Figure x.x** Schematic of imaging through a lens. The figure shows the object () and its image (), the object space principal plane () and the image side principal plane (), the entrance () and exit () pupils, and the associated distances along the optical axis. |

In the figure, and are the distances from the principal planes to the object and image planes, and are distances from the principal planes to the entrance- and exit-pupils and and are the distances from the entrance- and exit-pupils to the object and image planes. Since the entrance- and exit-pupil planes are conjugates, like the object and image planes, the Gaussian lens formula holds as follows:

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and

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The transverse magnification between the object and image planes is

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For images that are *real* and inverted, the transverse magnification is numerically negative since the directed distance is numerically negative, and is numerically positive.

The pupil magnification is defined as the ratio of the exit pupil diameter to the entrance pupil diameter. It is also the ratio between the exit pupil and entrance pupil distances (measured from the principal planes) just like the transverse magnification between any conjugate planes:

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Equating Eqs. (4.20) and (4.21), we obtain

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Substituting and in the above equation, and using Eqs. (4.22) and (4.23), we get

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Further, we can also substitute and in Eq. (4.20) and equate with Eq. (4.21) as

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which after cross-multiplication and cancellations of common terms produces

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Dividing throughout by, and substituting by the pupil magnification, and by we obtain:

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Eq. (4.25) is valid even if the and denote distances from the principal planes provided we let. This outcome is indeed consistent with geometric optics theory, according to which the magnification between the principal planes is unity. In fact, Eq. (3.40) is more general than the Gaussian Lens formula in that it relates a pair of conjugate planes with any other pair of conjugate planes for which the transverse magnification (between the planes) is known. When one of the pairs happen to be the principal planes ( and), between which the magnification is one, we obtain the Gaussian Lens formula.

Finally, we can also derive the equations for computing the entrance- and exit-pupil distances from the respective principal planes by substituting (4.23) into (4.21)

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### A brief account on the significance of pupil magnification

Although a pupil magnification close to one is a desirable property from the point of view of distortion in the presence of orientation misalignment, it seems to be hardly a critical design choice for most practical lenses except for those used for Scheimpflug photography as evident in plot of pupil magnifications in Figure x.x. In addition, the figure shows that telephoto lenses have pupil magnification less one and retrofocus wide-angle lenses have pupil magnification greater than one. This is because the telephoto lenses employ a negative focal length group near the sensor plane to make a long focal length lens in a compact body, which also results in a relatively smaller image of the stop in the image side compared to the image of the stop in the object side. That is, the entrance pupil is larger compared to the exit pupil in telephoto lenses resulting in pupil magnification less than one. On the other hand, a negative focal length group is placed at the front in short focal length retrofocus lenses to create space between the lens and sensor which results in larger exit pupil compared to the entrance pupil. Thus, the pupil magnification of retrofocus lenses are greater than one.

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| **Figure x.x** Pupil magnification in a wide variety of lenses that form *real* images. The figure demonstrates the absence of any correlation between pupil magnification and focal length. In addition, only 20 in the sample 120 (or one in six) lenses have pupil magnification in the range. Over 90% of all lenses have pupil magnification greater than 0.5. We obtained the samples from the Zemax Zebase library, which is a comprehensive catalogue of well-designed professional lenses. |

The F-number (or F/#) is the ratio of the effective focal length (distance between the image side principal plane to the image plane with the object at infinity) to the paraxial entrance-pupil diameter [ref]

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This infinite conjugate F-number is commonly specified by lens manufacturers and marked on lens bodies.

The pupil magnification is the ratio of the exit-pupil diameter to the entrance-pupil diameter

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Substituting from Eq. (4.28) into Eq. (4.27), we get

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When the object is at infinity, the distance between the image plane and the exit-pupil is obtained from Eq. (4.25) as

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Substituting in place of in Eq. (4.29) yields the alternative and equivalent definition for F-number—*as the ratio of the exit-pupil-to-image-plane distance to the exit-pupil diameter*:

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where is the distance from the exit-pupil to the image plane and is the diameter of the exit-pupil.

The F-number along with the wavelength determines the diffraction limited spatial resolution of optical imaging systems on the image plane as given by the equation [ref]

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For finite conjugate imaging, the object-plane-to-entrance-pupil distance decreases concomitant with an increase in exit-pupil-to-image-plane distance. This increase in the image plane distance effectively increases the F-number. The expression for the effective F-number is obtained as follows:

Substituting (where is the transverse magnification) from Eq. (4.24) into Eq. (4.25), followed by simple algebraic steps yields

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We have established that the F-number (for infinite conjugate) is the ratio of the exit-pupil-to-image-plane distance to the exit-pupil diameter. To obtain the effective F-number at finite conjugates, we substitute Eq. (4.33), the expression for the image-plane distance for finite conjugate imaging, into Eq. (4.31) :

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Further, substituting (Eq. (4.28)) and replacing with we get

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where is the transverse magnification (numerically negative for *real* images).

Now, we can obtain a more accurate equation for diffraction limited spatial resolution that is equally valid for both finite and infinite conjugate imaging by substituting Eq. (4.35) into Eq. (4.32)

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where is the wavelength, is the standard F-number defined for infinite conjugate imaging, is the pupil magnification, and is the transverse magnification (numerically negative for *real* images). When the object is at infinity, and Eq. (4.36) reduces to the optical resolution expression for infinite conjugate imaging.

To Investigate.

### Estimation of pupil locations, and pupil magnification

Describe why you would like to estimate these parameters

The entrance-pupil is the

Eliminating by substituting into Eq. (4.25) following simple algebraic manipulation we get

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where is the transverse magnification, is the distance of the object plane from the entrance-pupil, is the focal length. and are numerically negative for *real* images.

**TO DO**

1. Table showing different known equations that fall out of it. For example,
   1. thin lens, fronto-parallel imaging,
   2. thin lens image plane tilt model,
   3. thin lens image and lens tilt model,
   4. thick lens model, etc.
2. Zemax based verification
3. Analysis of the “image” equation
   1. with regards to collinear transformation
   2. Deductions from it in terms of image plane magnification, and image distortions.
4. Discussions about Tilt about entrance pupil vs. tilt about the principal point.
5. Justifications for this formulation (provide evidence for the efficacy of this formulation).
   1. Distances measured from entrance and exit pupils. The entrance pupil is easily locatable with simple experiments. The in diffraction based calculations, the exit pupil is of vital importance, as aberrations, and resolutions are specified w.r.t. the exit pupil.

1. In the presence of spherical aberrations, the chief ray goes through the center of the aperture but may not exactly go through the center of the pupils [Ref Mirrors, Prisms … Southall, Lens design by Kingslake]. [↑](#footnote-ref-1)