# Chapter 3

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

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. These cameras find use in few scientific imaging applications, but the vast majority of them contemporarily are used for landscape and studio photography.

Existing models of Scheimpflug camera employ simple....by imposing/restricting…. While these models work quite well for documentary photography, they 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 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. We have assumed paraxial imaging, rotational symmetry and aberration-free optics. Additionally, 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: Describe the Scheimpflug camera in two sentences.

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, and those elements with optical power bends rays of light. The *system aperture* or *stop* is the tiniest orifice in the system whose 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. 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 3.1 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 3.1** 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

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

The *pupil magnification*, is defined as the ratio of the paraxial exit pupil size to the entrance pupil size [refref]. Figure 3.2 illustrates the meridional and sagittal planes associated with an arbitrarily located object of height units 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 3.2** 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 produced by the chief ray with 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 the pupil magnification as follows:

From the Figure 3.2,

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Eliminating and after dividing by , we have

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As per the *Lagrange invariant* [ref] property of the two rays at the location of the object and the image,. Therefore

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The equation (3.2), has been previously derived in [ref] using a different formulation. For a given optics 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]. Equation (3.2) also suggests that when the perspective cones in the object- and image-space are symmetric. In the following section, we will use equation (3.2) 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 what is 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 3.3. 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 3.3** 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 equation (3.3) into equation (3.2) 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 (3.2) we have

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

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Combining equations (3.5) and (3.7), 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 3.4. Although a formal derivation is provided in [Appendix], we can readily infer the general *transfer* expression from equation (3.9) 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 equation (3.9):

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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 3.4** 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 equation (3.10); 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 equation (3.11) 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 (3.11), we expect to have unit magnitude. We have provided a proof in [Appendix] that shows the (magnitude) of equal one, and is the normalizing term.

We can draw the following inferences about from the equation (3.11):

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. Therefore, we can find a plane perpendicular to the optical axis about which the lens is symmetric. Such lenses are can be reversed without affecting system properties, and are called symmetric lenses [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 equation (3.12) 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 world to 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” when the pencil of rays from the world-point, filling the pupils and stop geometrically, converge at a single point in the image space.

We assume that the lens is unencumbered by radial distortions and optical aberrations. Figure 3.5 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 introduced: the frame is fixed to the optical axis with its origin at entrance pupil, and the frame fixed to the image plane with its origin at the intersection of the image plane with the z-axis of the camera frame. The origin of also represents the pivot point about which the image plane is free to swivel (tilt or swing about its local x-axis or y-axis respectively).

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| **Figure 3.5** 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 .

The parametric equation of the chief ray emerging from the exit pupil with direction cosine is then represented as:

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where represents any point along the output chief ray in . The first term on the R.H.S. of (3.13) the 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 given as:

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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 arbitary point on the plane.

We obtain the expression for for which the ray intersects the image plane by equating to, multiplying equation (3.13) by, and rearranging the terms:

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Substituting (3.15) into (3.13):

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As previously stated, the origin of , the image plane’s local reference frame, is located at the intersection of the z-axis of with the image plane. The orientation of the image plane can be described by applying a rotation matrix (or a composition of successive rotation matrices) to the image plane, with its unit plane-normal nominally equal to , about the origin of as shown in Figure 3.5. If is the rotation matrix then

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Referring to Figure 3.6, the expression for is obtained as follows:

The equation of the image plane is

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Since is a point on the plane,

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| **Figure 3.6** 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, the expression for the point of intersection of the chief ray with the image plane in terms of the input direction cosines is

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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 equation (3.21) into equation (3.19) a general relation between the world point and its corresponding image point is obtained:

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Equation (3.22) represents the image point in the camera frame. Once an image is formed, we specify positions and dimensions within the image independent of the position and orientation of the sensor and lenses. 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 . Therefore a point in relative to may be expressed as:

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Let and be the homogeneous representation [ref] of the and respectively. The equation (3.23) can be expressed as a linear matrix operation as:

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where is the pose of with respect to frame . Then, it follows that

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where.

Finally, we obtain the image coordinates in the image frame as:

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

Section introduction.

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, the object plane is completely described by this point and its normal, . The object plane normal itself is described as the product of a three dimensional rotation matrix and (). The left superscript ‘O’ in indicates that the matrix is applied about , the pivot point of the object plane, along the z-axis of .

Equation of the object plane normal:

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Equation of the object plane, in Hessian Normal form:

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where is any point on the object plane.

Since the image plane is pivoted about the point in the z-axis of the camera frame , we can ascribe the following relations for the image plane.

Equation of the image plane normal:

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where is the rotation matrix applied to the image plane at the point along the z-axis of .

The, the equation of the image plane, in Hessian Normal form is:

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where is any point on the image plane.

Let the entrance () and exit () pupils be located at and units from the optical axis’ pivot point (origin of ), respectively, along the optical axis. If we describe the rotation of the optical axis by the matrix , then, following the rotation, the position of the pupils in is given as:

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In the following sections we have dropped the left superscripts from the rotation matrices keeping in mind that the three rotation matrices—,, and —are applied about the respective pivot points of the object, lens and image planes.

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 coincident with the chief 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 (i.e. the chief ray), is the position of the entrance pupil, and the parameter determines the length of the line segment.

Let the length of the ray between the object-point and the entrance pupil be. Then, in equation (3.33), when, which implies that

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Since is a point on the object plane, it satisfies the object plane equation (3.28). Substituting into equation (3.28) 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 the point to the right (positive z direction) of the exit pupil. 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 line segment.

If the length of the ray between the exit pupil and the image point is, then when in equation (3.36), implying

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and, from equation (3.30),

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TO DO:

1. Table showing different known equations that fall out of it. For example, a) thin lens, fronto-parallel imaging, b) thin-lens image plane tilt model, c) thin-lens image and lens tilt model, d) thick lens model, etc.
2. Zemax based verification
3. Analysis of the equation, especially with regards to collinear transformation
4. Tilt about entrance pupil vs. tilt about the principal point.

# 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.

Equation (3.8) 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 equations (3.8) and (4.2):

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Substituting the expression for into and comparing with (3.7) 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 equation (4.5) is different from the corresponding in equation (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 equation (4.5) by:

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Letting and,

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Comparing equations (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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Therefore, since is the third element of .

Rewriting equation (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 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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Substituting in equation (4.15),

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Substituting into equation (4.14) we have

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It follows that the scalar quantity is the normalization term. Q.E.D.

### Derivation 3.2 Gaussian lens formula with pupil magnification

The familiar Gaussian lens formula, , shows the relationship between the conjugate planes in which is the distance between the object plane (perpendicular to the optical axis) and the principal plane () in the object space, is the distance between the in-focus image plane and the principal plane () in the image space, and is the focal length of the lens. 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 is derived in [Ref] using a slightly different approach.

Figure xxx shows a schematic …..

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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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The pupil magnification, , defined as the ratio of the exit pupil diameter to the entrance pupil diameter, 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:

|  |  |
| --- | --- |
|  |  |

Equating equations (4.20) and (4.21), we obtain

|  |  |
| --- | --- |
|  |  |

Substituting and in the above equation, and using equations (4.22) and (4.23):

|  |  |
| --- | --- |
|  |  |

Further, we can also substitute and in equation (4.20) and equate with equation (4.21):

|  |  |
| --- | --- |
|  |  |

which after cross-multiplication and cancellations of common terms produces

|  |  |
| --- | --- |
|  |  |

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

|  |  |
| --- | --- |
|  |  |

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)