NEW METHODS FOR WIDE-BASELINE IMAGE INTERPOLATION

by

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To all those who were told they couldn't ...

... but persevered, and did anyways.

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COMMONLY USED SYMBOLS AND NOTATION

Symbol	**Description**
$\mathbf{v}$	*Vectors* in *lowercase* bold
v_a	a-component of vector $\mathbf{v}$
$v_{a/b}$	The ratio of vector v's a-component to it's b-component
$\mathbf{M}$	*Matrices* in *uppercase* bold
$\tilde{\mathbf{M}}$	Matrix $\mathbf{M}$ expressed homogeneously such that *right lowermost* entry equals 1
$M_{r,c}$	*Entry* in row r and column c of matrix $\mathbf{M}$
$\mathbf{m}_c$	*Vector* occurring in column c of matrix $\mathbf{M}$
$\mathbf{x}$	Generic 3-dimensional spatial coordinate
$\tilde{\mathbf{x}}$	Generic 3-dimensional spatial coordinate (expressed *homogeneously*)
$\mathbf{y}$	Generic 2-dimensionals image coordinate
$\tilde{\mathbf{y}}$	Generic 2-dimensional image coordinate (expressed *homogeneously*)
$\mathbf{u}$	Pixelized 2-dimensional image coordinate
$\tilde{\mathbf{u}}$	Pixelized 2-dimensional image coordinate (expressed *homogeneously*)
${}^A\mathbf{x}$	Generic 3-dimensional spatial coordinate in reference frame A
${}^A\tilde{\mathbf{x}}$	Generic 3-dimensional spatial coordinate (expressed *homogeneously*) in reference frame A

${}^{C}_{B}\tilde{\mathbf{M}}$	Change from of reference frame B to reference frame C
$\cong$	*Equal to to a scale factor*. Used in $\mathbf{v} \cong \tilde{\mathbf{v}} \iff \mathbf{v} = s \cdot \tilde{\mathbf{v}}$ or $\mathbf{M} \cong \tilde{\mathbf{M}} \iff \mathbf{M} = s \cdot \tilde{\mathbf{M}}$
f	*focal-length*
s	*Scalar* applied to *homogeneous vector* $\tilde{\mathbf{v}}$ or *homogenous matrix* $\tilde{\mathbf{M}}$ such that original $\mathbf{v} = s \cdot \tilde{\mathbf{v}}$ or $\mathbf{M} = s \cdot \tilde{\mathbf{M}}$ is recovered
${}^{D}\mathbb{S}$	Spatial reference frame D
$[\mathbf{x}]_{\times}$	Skew-symmetric matrix version of vector $\mathbf{x}$ used as *left*-operand in the *cross*-product such that $[\mathbf{x}]_{\times} \cdot \mathbf{y} = \mathbf{x} \times \mathbf{y}$
$\mathbf{l}$	Epipolar line (expressed as *vector*
$\mathbb{P}$	Ray (or *pencil*) of all possible vectors $\mathbf{x}$ where $\mathbf{x} = s \cdot \tilde{\mathbf{x}}$ for some value of s

CHAPTER 1

Background

Oridinarily, real-world data contains 3-dimensions. Because standard images only include 2-dimensional data, information regarding depth is lost (i.e. it is often difficult to judge distance from a single image without visual cues). *Stereovision* attempts to resolved this by finding the same point in both *stereoscopic* images (known as a *corresponding point*), and recovering the depth information. An elementry example of this occurs in stereoscopic images with relatively low distance between cameras (i.e they are righht next to each other). Objects that are *farther* away from the observer occur closer together in the stereo images, whereas objects *closer* to the camera appear appear farther appart in the stereo-images.

1.1 Change of Reference

Each view from a pair of stereo-images encompasses its own *frame of reference* (i.e. the directions of *forward* or *backward* are unique to image and may differe considerably depending on camera displacement). As such it is necessary to be able to express on coordinates ${}^{A}\mathbf{x}$ a given reference frame as coordinates ${}^{B}\mathbf{x}$ in another reference frame.

Coordinates given in ${}^{A}\mathbf{x}$ can be expressed in ${}^{B}\mathbf{x}$ by the geometric transformation:

$$ {}^{B}\mathbf{x} = {}^{B}_{A}\mathbf{R} \cdot {}^{A}\mathbf{x} + {}^{B}_{A}\mathbf{t} $$

or

$$
{}^{B}\tilde{\mathbf{x}} = \left[\begin{array}{c|c} {}^{B}_{A}\mathbf{R} & {}^{B}_{A}\mathbf{t} \\ \hline 0 & 1 \end{array}\right] \cdot {}^{A}\tilde{\mathbf{x}}
$$

$$
= {}^{B}_{A}\mathbf{M} \cdot {}^{A}\tilde{\mathbf{x}}
$$

where ${}^{B}_{A}\mathbf{M}$ is also the geometric transformation necessary to transform ${}^{B}\mathbb{S}$ into ${}^{A}\mathbb{S}$. Without calculating any new quantities, rearranging allows us to express coordinates in ${}^{B}\mathbf{x}$ in the ${}^{A}\mathbf{x}$ reference frame as:

$$
{}^{B}_{A}\mathbf{R}^{\intercal} \cdot ({}^{B}\mathbf{x} - {}^{B}_{A}\mathbf{t}) = {}^{A}\mathbf{x}
$$

and similarly transforms ${}^{A}\mathbb{S}$ into ${}^{B}\mathbb{S}$.

1.2 Points and Lines in the Image Plane

Points in *world-space* of $\mathbb{R}^3$ are converted to points in the *image-plane* of $\mathbb{R}^2$ by *homogenization*. This occurs when a *world-coordinate* of $\mathbf{x} = [x_1, x_2, x_3]^{\intercal}$ is mapped to a *homogeneous image coordinate* of $\tilde{\mathbf{y}} = [y_1, y_2, 1]^{\intercal} = [x_1/x_3,\ x_2/x_3,\ x_3/x_3]^{\intercal}$ or a *non-homogeneous image coordinate* of $\mathbf{y} = [y_1, y_2]^{\intercal} = [x_1/x_3,\ x_2/x_3]^{\intercal}$. Points of the form $\tilde{\mathbf{y}} = [y_1, y_2, 0]^{\intercal}$ are special case of homogeneous point referred to as a *point at infinity*.

Lines in $\mathbb{R}^2$ can be represented in different contexts. The *vector offset* method calculates a line $\mathbf{s}(t)$ between points $\mathbf{y_1}$ and $\mathbf{y_2}$ as

$$
\begin{aligned}
\mathbf{s}(t) &= (1-t) \cdot \mathbf{y_1} + t \cdot \mathbf{y_2} \\
&= \mathbf{y_1} + t \cdot (\mathbf{y_2} - \mathbf{y_1})
\end{aligned}
$$

in which the line is parrallel to the vector $\mathbf{y_2} - \mathbf{y_1}$ and offset from the origin by the vector $\mathbf{y_1}$. Lines are also represented by their coefficients as $\mathbf{l} = [a, b, c]^\intercal$ where

$$\mathbf{l}^\intercal \cdot \tilde{\mathbf{y}} = \begin{bmatrix} a & b & c \end{bmatrix} \cdot \begin{bmatrix} y_1 \\ y_2 \\ 1 \end{bmatrix}$$
$$= a \cdot y_1 + b \cdot y_2 + c \cdot 1$$
$$= 0$$

This definition lets us say $\tilde{\mathbf{y}}$ is located on line $\mathbf{l}$ *if and only if* $\mathbf{l}^\intercal \cdot \tilde{\mathbf{y}} = 0$. The line $\mathbf{l}$ joining two *homogeneous image coordinates* $\tilde{\mathbf{y}}_\mathbf{1}$ and $\tilde{\mathbf{y}}_\mathbf{2}$ is then calculated as the cross product of $\mathbf{l} = \tilde{\mathbf{y}}_\mathbf{1} \times \tilde{\mathbf{y}}_\mathbf{2}$.

1.3 Epipolar Geometry

Each point of of interest (also referred to as a *feature*) in a single image occurs in a 2-dimensional space at location $\tilde{\mathbf{y}} = [x, y, 1]^\intercal$. The same point in space when viewed from an image at a similar (though different) angle is referred to as a *corresponding point* with location of $\tilde{\mathbf{y}}' = [x', y', 1]^\intercal$[1]. This set of infinitley many points form a 1-dimensional subspace (also known as a *pencil*) of the 3-dimensional world space.

The pencil, when viewed from an image at a different angled-position, appears as a line $\mathbf{l}' = [A', B', C']^\intercal$, known as the *epipolar line.* The fact that the corresponding point (in the *angled image*) of $\tilde{\mathbf{y}}' = [x', y', 1]^\intercal$ occurs on this epipolar line is referred to as the *epipolar constraint.* It is formalized, using the previously given *line-point equality* of $\mathbf{l}'^\intercal \cdot \tilde{\mathbf{y}}' = 0$ for the *angled* image. Similarly, the corresponding point of

[1]A *change of reference* is implied between cooridinates $\tilde{\mathbf{y}} = [x', y', 1]^\intercal$ and $\tilde{\mathbf{y}}' = [x', y', 1]^\intercal$. The majority of corresponding points do not occur at the same *image coordinates* between images (i.e $\tilde{\mathbf{y}} \neq \tilde{\mathbf{y}}'$. The only way a single *world coordinate* can yield different *image coordinates*, is if a *change of reference* occurs in *world space* each time the *image coordinates* are obtained by dividing by z_{world}.

$\tilde{\mathbf{y}}' = [x', y', 1]^\intercal$ produces an epipolar line in the *original image* of $\mathbf{l} = [A, B, C]$. The original point of $\tilde{\mathbf{y}} = [x, y, 1]^\intercal$ must lie located on this epipolar line as required by the epipolar constraint, resulting in the *line-point equality* of $\mathbf{l}^\intercal \cdot \tilde{\mathbf{y}} = 0$ for the *original image*.

When viewed in ther respective images, each point ($\tilde{\mathbf{y}}$ and $\tilde{\mathbf{y}}'$) has a pencil that coincides with that point. Since the pencils act as *directional*-vectors in 3-dimensional space, there is a unique 2-dimensional plane which contain both of these vectors, known as the *epipolar plane*. It is the intersection of the epipolar plane with the *original image*-plane and the *angled image*-plane that results in the epipolar lines of $\mathbf{l}$ and $\mathbf{l}'$, respectively. In fact, the *epipolar plane* (in each image's *coordinate systems*)[2] has the same vector form as its epipolar line. Specifically, in the *original image* reference frame $\mathbf{l} = \mathbf{P} = [A, B, C]^\intercal$, and in the *angled image* reference frame $\mathbf{l}' = \mathbf{P}' = [A', B', C']^\intercal$. This results from the fact that any *world*-point $\mathbf{x}$ lying on the *epipolar plane* $\mathbf{P}$ will result in a *homogeneous image*-point $\tilde{\mathbf{y}}$ that also lies on the plane $\mathbf{P}$. Specifically, when $\mathbf{x} = s \cdot \tilde{\mathbf{y}}$ for some non-zero value of s, then $\mathbf{P}^\intercal \cdot \mathbf{x} = 0$ implies $\mathbf{P}^\intercal \cdot \mathbf{x} = \mathbf{P}^\intercal \cdot (s \cdot \tilde{\mathbf{y}}) = 0$. Since $s \neq 0$, its true that $\mathbf{P}^\intercal \cdot \tilde{\mathbf{y}} = 0$.

In the majority of images, the sets of epipolar lines will converge at a point known as an *epipole*, denoted as $\mathbf{e}$ in the *original image* and $\mathbf{e}'$ in the *angled image*.

1.4 Fundamental Matrix

In stereo vision, points ($\tilde{\mathbf{x}}$) in one image I are related to the epipolar line (l') that contain the corresponding point ($\tilde{\mathbf{x}}'$) by the *Fundamental Matrix* ($\mathbf{F}$).

$$l' = \mathbf{F} \cdot \tilde{\mathbf{x}}$$

[2] There is a single *epipolar plane* for each pair of corresponding points $\tilde{\mathbf{y}}$ and $\tilde{\mathbf{y}}'$. However, the single plane can be parameterized infinitley many ways, depending on the *frame of reference*

1.4.1 Theoretical Calculation

1.4.2 Calculation from Data

Calculation of the *Fundamental Matrix* through theoretical metods may be difficult due to the abscense of parameters or through errors introduced in the use of pixelized points common in digtial cameras. As previously mentioned, the fundamental matrix $\mathbf{F}$ for points $\tilde{\mathbf{y}}_i = [y_{i1}, y_{i2}, 1]^\intercal$ and $\tilde{\mathbf{y}}'_i = [y'_{i1}, y'_{i2}, 1]^\intercal$ (for all i) is represented as the formula $0 = \tilde{\mathbf{y}}_i'^\intercal \cdot \mathbf{F} \cdot \tilde{\mathbf{y}}_i$. Rearranging this gives:

$$
\begin{aligned}
0 &= \tilde{\mathbf{y}}_i'^\intercal \cdot \mathbf{F} \cdot \tilde{\mathbf{y}}_i \\
&= \begin{bmatrix} y'_{i1} & y'_{i2} & 1 \end{bmatrix} \begin{bmatrix} f_1 & f_2 & f_3 \\ f_4 & f_5 & f_6 \\ f_7 & f_8 & f_9 \end{bmatrix} \begin{bmatrix} y_{i1} \\ y_{i2} \\ 1 \end{bmatrix}
\end{aligned}
$$

which when the matrices are multiplied, gives

$$
\begin{aligned}
0 &= \begin{bmatrix} y'_{i1} & y'_{i2} & 1 \end{bmatrix} \begin{bmatrix} f_1 \cdot y_{i1} + f_2 \cdot y_{i2} + f_3 \\ f_4 \cdot y_{i1} + f_5 \cdot y_{i2} + f_6 \\ f_7 \cdot y_{i1} + f_8 \cdot y_{i2} + f_9 \end{bmatrix} \\
&= \begin{bmatrix} f_1 \cdot y_{i1} \cdot y'_{i1} & + & f_2 \cdot y_{i2} \cdot y'_{i1} & + & f_3 \cdot y'_{i1} & + \\ f_4 \cdot y_{i1} \cdot y'_{i2} & + & f_5 \cdot y_{i2} \cdot y'_{i2} & + & f_6 \cdot y'_{i2} & + \\ f_7 \cdot y_{i1} & + & f_8 \cdot y_{i2} & + & f_9 \cdot 1 & \end{bmatrix}
\end{aligned}
$$

and a factored form of

$$0 = \begin{bmatrix} y_{i1} \cdot y'_{i1} & y_{i2} \cdot y'_{i1} & y'_{i1} & y_{i1} \cdot y'_{i2} & y_{i2} \cdot y'_{i2} & y'_{i2} & y_{i1} & y_{i2} & 1 \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 \\ f_7 \\ f_8 \\ f_9 \end{bmatrix} = \mathbf{m}_i^{\intercal} \cdot \mathbf{f}$$

The *fundamental matrix (in vector form)* $\mathbf{f}$ is then calculated as the *null space* (or closest possible equivalent) of the collection $\mathbf{M}_n$ of all n pairs of points $\mathbf{m}_i^{\intercal}$ since

$$\mathbf{0} = \begin{bmatrix} \mathbf{m}_1^{\intercal} \\ \mathbf{m}_2^{\intercal} \\ \vdots \\ \mathbf{m}_n^{\intercal} \end{bmatrix} \cdot \mathbf{f} = \mathbf{M}_n \cdot \mathbf{f}$$

The vector $\mathbf{f}$ that results in product $\mathbf{M}_i \cdot \mathbf{f}$ closest to the zero vector $\mathbf{0}$ can then be calculated through *linear least squares* through the *singular value decomposition* of $\mathbf{M}_i$. The vector $\mathbf{f}$ is calculated as the *singular vector* of $\mathbf{M}$ with the smallest *singular value* [1].

1.5 Camera Calibration Matrix

1.5.1 Pinhole Camera Model

A point $\mathbf{x}$ in the *camera-coordinate system* of $\mathbb{R}^3$ is projected to the point $\tilde{\mathbf{y}}$ in $\mathbb{R}^2$ by means of the *pinhole camera model.* The set of all $\tilde{\mathbf{y}}$ are the result of *rays* passing through the *image plane* located at $z = f$, and converging at the *optical center* as shown in the figure below:

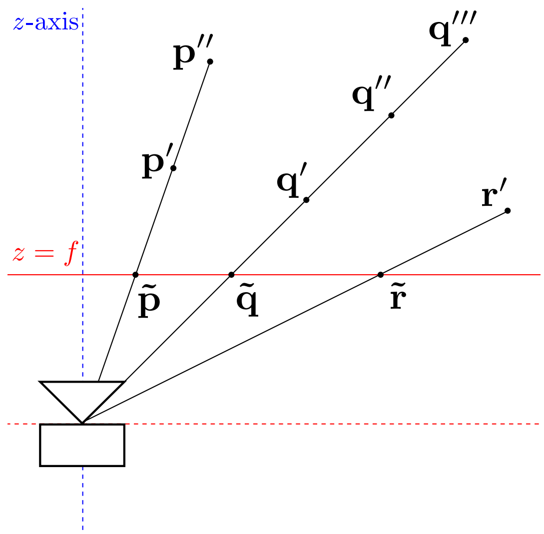

Figure 1.1. Pinhole CameraModel.

The exact location that $\tilde{\mathbf{y}}$ appears on the image plane is determined by utilizing the *similarity of triangles* between $\mathbf{x}$ and $\tilde{\mathbf{y}}$. Specifically, we see that $y_1/f = x_1/x_3$ and $y_2/f = x_2/x_3$ rearranged gives $x_3 \cdot y_1 = f \cdot x_1$ and $x_3 \cdot y_2 = f \cdot x_2$. This lets us relate $\tilde{\mathbf{x}}$ and $\tilde{\mathbf{y}}$ by the *projection matrix* $\mathbf{P}$ as

$$x_3 \cdot \tilde{\mathbf{y}} = \left[\begin{array}{c|c} \mathbf{P} & 0 \end{array}\right] \cdot \tilde{\mathbf{x}} = \left[\begin{array}{ccc|c} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{array}\right] \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ 1 \end{bmatrix}$$

Since, for a given $\tilde{\mathbf{x}}$ in *camera space*, the quantities $x_{1/3} = x_1/x_3$ and $x_{2/3} = x_2/x_3$ are *invariant under the scale of* $\tilde{\mathbf{x}}$, the location of $\tilde{\mathbf{y}}$ in the *image plane* depends only on the ratios $x_{1/3}$ and $x_{2/3}$ and the quantity f. This yields a similar form, obtained from dividing by x_3, of

$$\tilde{\mathbf{y}} = \frac{l}{x_3} \left[\mathbf{P} \,\middle|\, 0 \right] \cdot \tilde{\mathbf{x}} = \left[\begin{array}{ccc|c} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{array} \right] \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ 1 \end{bmatrix} = \left[\begin{array}{ccc|c} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{array} \right] \cdot \begin{bmatrix} x_1/x_3 \\ x_2/x_3 \\ x_3/x_3 \\ 1 \end{bmatrix}$$

This results in *camera space* points $\tilde{\mathbf{x}}$ with similar values of x_1 and x_2, but containing infinitley large values of x_3 being mapped to the same point $\tilde{\mathbf{y}}$ in the *image plane*. This point $\mathbf{y} = 0$ is referred to as the *principal point* (or *center of projection*)in the *image plane*, and sometimes appears as a *vanishing point* for fixed values of x_1 and x_2, but *infinitley increasing* values of x_3.

1.5.2 Intrinsic Calibration Matrix

Points $\tilde{\mathbf{y}}$ given in the *image plane* have the same *units of measure* (or *scale*) as the points $\tilde{\mathbf{x}}$ in *camera space*. When dealing with digital images it's often more convenient to express *image coordinates* in terms of units such as *pixels* rather than real world units such as *inches*, *feet*, or *meters*. The matrix $\mathbf{K}$, where

$$\mathbf{K} = \begin{bmatrix} k_u & 0 & p_u \\ 0 & k_v & p_v \\ 0 & 0 & 1 \end{bmatrix}$$

is used to parameterize an image point $\tilde{\mathbf{u}}$ (in *pixels*), as a function of the coordinates $\mathbf{x}$ in *camera space* and the *camera specific parameters* of *horizontal pixel resolution* k_u, *vertical pixel resolution* k_v, and *principal point* $\mathbf{p} = [p_x, p_y]^\intercal$. When combined with the additional camera specific parameter of *focal length* f in the *projection matrix* $\mathbf{P}$, the result is

$$\begin{aligned}\mathbf{Q} &= \mathbf{K} \cdot \mathbf{P} \\ &= \begin{bmatrix} k_u & 0 & p_u \\ 0 & k_v & p_v \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} f \cdot k_u & 0 & p_u \\ 0 & f \cdot k_v & p_v \\ 0 & 0 & 1 \end{bmatrix}\end{aligned}$$

which lets us relate the *pixel point* $\tilde{\mathbf{u}}$ to a point $\tilde{\mathbf{x}}$ in *camera space* as

$$\tilde{\mathbf{u}} = \mathbf{K} \cdot \tilde{\mathbf{y}} \cong \mathbf{K} \cdot \left[\begin{array}{c|c} \mathbf{P} & 0 \end{array}\right] \cdot \tilde{\mathbf{x}} = \left[\begin{array}{c|c} \mathbf{Q} & 0 \end{array}\right] \cdot \tilde{\mathbf{x}} = \mathbf{Q} \cdot \left[\begin{array}{c|c} \mathbf{I} & 0 \end{array}\right] \cdot \tilde{\mathbf{x}}$$

where $\mathbf{Q}$ is referred to as the *camera calibration matrix.* Since $\mathbf{Q}$ is dependant only on parameters *internal to the camera*, its also referred to as the *intrinsic calibration matrix.*

1.5.3 Extrinsic Calibration Matrix

Use of *pinhole camera model* by itself requires several assumptions being made, namely that the optical center $\mathbf{C}$ occurs at the origin, and that the *image plane* is placed at $z = f$ (is parallel to xy-plane). This implies the *camera space* is coincident with *world space*, or that the *camera*-coordinate and *world*-coordinate systems are one and the same. In simple scenes, this may not present a problem. In more complex scenes, including those with multiple cameras, this requires using the *pinhole camera model* in the context of an arbitary *world space.* This can be accomplished through the previously discussed *change of reference.*

As previously discussed, the *change of reference* from a *world coordinate* ${}^{W}\mathbf{x}$ to a *camera coordinate* ${}^{C}\mathbf{x}$ is calculated by the formula

$$ {}^{C}\mathbf{x} = {}^{C}_{W}\mathbf{R} \cdot {}^{W}\mathbf{x} + {}^{C}_{W}\mathbf{t} $$

or *homogeneously* as

$$ \begin{aligned} {}^{C}\tilde{\mathbf{x}} &= \left[\begin{array}{c|c} {}^{C}_{W}\mathbf{R} & {}^{C}_{W}\mathbf{t} \\ \hline 0 & 1 \end{array} \right] \cdot {}^{W}\tilde{\mathbf{x}} \\ &= {}^{C}_{W}\tilde{\mathbf{M}} \cdot {}^{W}\tilde{\mathbf{x}} \end{aligned} $$

which allows us to project *world coordinates* ${}^{W}\tilde{\mathbf{x}}$ to the *pixel coordinates* $\tilde{\mathbf{u}}$ in the *image plane* as

$$ \tilde{\mathbf{u}} \cong \mathbf{Q} \cdot \left[\begin{array}{c|c} \mathbf{I} & 0 \end{array} \right] \cdot {}^{C}\tilde{\mathbf{x}} = \mathbf{Q} \cdot \left[\begin{array}{c|c} \mathbf{I} & 0 \end{array} \right] \cdot {}^{C}_{W}\tilde{\mathbf{M}} \cdot {}^{W}\tilde{\mathbf{x}} $$

Since the matrix ${}^{C}_{W}\tilde{\mathbf{M}}$ is dependent only on the relative position and orientation of the *camera* (rather than the camera itself) it is commonly referred to as the *extrinsic calibration matrix.*

1.6 Essential Matrix

When coordinates from a reference frame are expressed as *normalized image coordinates* the range of possible NIC values in the corresponding image are given by the

CHAPTER 2

Rectification

REFERENCES

[1] R. I. Hartley and A. Zisserman, *Multiple View Geometry in Computer Vision*, 2nd ed. Cambridge University Press, ISBN: 0521540518, 2004.

BIOGRAPHICAL STATEMENT

Jeff G. Wood was born in Evanston, Illinois, in 1981. He received his B.A. degree in Mathematics from Clarke College (now Clarke University) in Dubuque, Iowa, in 2003. Since that time, has worked as an actuary pricing Universal Life and Longterm Care insurance. He is a member of the Tau Beta Pi and Upsilon Pi Epsilon honor societies as well as the Association of Computing Machinary society.