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 $\mathbf{v}$
$\mathbf{M}$	*Matrices* in *uppercase* bold
$M_{r,c}$	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 $\mathbf{v} \cong \tilde{\mathbf{v}} \iff \mathbf{v} = s \cdot \tilde{\mathbf{v}}$
f	*focal-length*

s	*Scalar* applied to *homogeneous* vector $\tilde{\mathbf{v}}$ such that original $\mathbf{v} = s \cdot \tilde{\mathbf{v}}$ 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 $[\mathbf{x}]_\times \cdot \mathbf{y} = \mathbf{x} \times \mathbf{y}$
l	Epipolar line
$\mathbb{P}$	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). This requires expressing points from different frames of reference (traditionally referred to *left* and *right*) in a single reference frame. As such it is necessary to be able to express coordinates in a given reference frame in any other 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 ${}^{A}\mathbb{S}$.

Withough 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

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

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.

[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}.

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 $\tilde{\mathbf{y}}' = [x', y', 1]^\intercal$ 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* $\mathbf{e}'$ in the *angled image*.

[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 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* ($\mathbf{F}$).

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

1.5 Intrinsic Calibration Matrix

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:

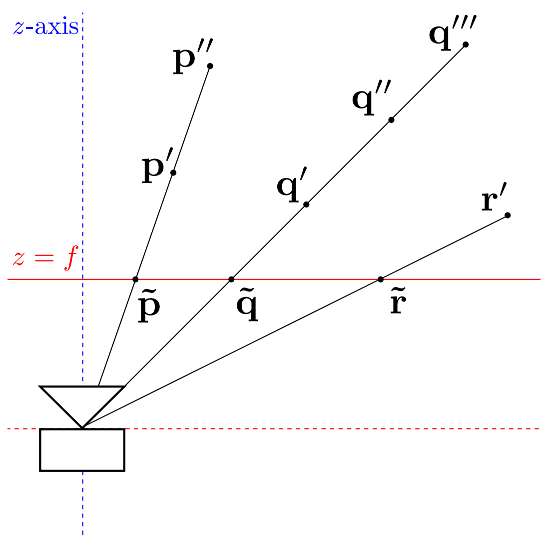

Figure 1.1. Pinhole CameraModel.

The location of $\tilde{\mathbf{y}}$ 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 $y_2/f = x_2/x_3$ lets us exprss the *image coordinate* $\tilde{\mathbf{y}}$ as $y_1 = f \cdot x_1/x_3$ and $y_2 = f \cdot x_2/x_3$. The point in the *image plane* of $\tilde{\mathbf{y}}$

is derived from the point $\mathbf{x}$ in *camera space* by means of the the *Camera Projection Matrix* $\mathbf{P}$ such that

$$
\begin{aligned}
\mathbf{P} \cdot \tilde{\mathbf{x}} &= \begin{bmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ 1 \end{bmatrix} = \begin{bmatrix} f \cdot x_1 \\ f \cdot x_2 \\ x_3 \end{bmatrix} \\
&= x_3 \cdot \begin{bmatrix} f \cdot x_1/x_3 \\ f \cdot x_2/x_3 \\ 1 \end{bmatrix} = x_3 \cdot \tilde{\mathbf{y}}
\end{aligned}
$$

This results in points $\tilde{\mathbf{x}}$ 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* in the *image plane*. This assumes the *principal point* is always located in the *image plane* at $\mathbf{y} = 0$. Projecting point $\tilde{\mathbf{x}}$ to the *image plane* with arbitrary *principal point* $\mathbf{p} = [p_x, p_y]^\intercal$ requires modifying the *projection matrix* to include *camera-specific* parameters. The *camera calibration matrix* $\mathbf{K}$ is given as

$$
\begin{aligned}
\mathbf{P} \cdot \tilde{\mathbf{x}} &= \begin{bmatrix} f & 0 & p_x & 0 \\ 0 & f & p_y & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ 1 \end{bmatrix} = \begin{bmatrix} f \cdot x_1 + p_x \cdot x_3 \\ f \cdot x_2 + p_y \cdot x_3 \\ x_3 \end{bmatrix} \\
&= x_3 \cdot \begin{bmatrix} f \cdot x_1/x_3 + p_x \\ f \cdot x_2/x_3 + p_y \\ 1 \end{bmatrix} = x_3 \cdot \tilde{\mathbf{y}}
\end{aligned}
$$

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

REFERENCES

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.