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Correcting Radial Distortion of Cameras with Wide Angle Lens Using Point Correspondences

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1. Introduction

Most algorithms in 3-D Computer Vision rely on the pinhole camera model because of its simplicity, whereas video optics, especially wide-angle lens, generates a lot of non-linear distortion. In some applications, for instance in stereo vision systems and robotic systems, this distortion can be critical.

Camera calibration consists of finding the mapping between the 3-D space and the camera plane. This mapping can be separated into two different transformations: first, the relation between the origin of 3-D space (the global coordinate system) and the camera coordinate system, which forms the external calibration parameters (3-D rotation and translation), and second the mapping between 3-D points in space (using the camera coordinate system) and 2-D points on the camera plane, which forms the internal calibration parameters (Devernay & Faugeras, 1995).

Fig. 1 shows two types of distortion due to lens: barrel and pincushion distortions and a rectangle without any distortion like reference (e.g. the image taken by an ideal pinhole camera) (Weng et al. 1992). The pincushion distortion is due to zoom lens and the barrel distortion is due to wide angle lens. In commercial cameras with wide angle lens the most important component of the barrel distortion is the radial distortion and this chapter introduces a method to find the internal calibration parameters of a camera, specifically those parameters required to correct the radial distortion due to wide-angle lens.

Figure 1. Types of distortion

The method works with two images, one from the camera and one from a calibration pattern (without distortion) and it is based on a non-linear optimization method to match feature points of both images, given a parametric distortion model. The image from the calibration pattern can be a scanned image, an image taken by a high quality digital camera (without lens distortion), or even the binary image of the pattern (which printed becomes the pattern).

First, a set of feature point correspondences between both images are computed automatically. The next step is to find the best distortion model that maps the feature points from the distorted image to the calibration pattern. This search is guided by analytical derivatives with respect to the set of calibration parameters. The final result is the set of parameters of the best distortion model.

The rest of this chapter is organized as follows. Section 2 describes the problem to compute transformed images and it presents the Bilinear Interpolation as a solution to that problem. Sections 3 and 4 describe the distortion and projective model that we are using. Section 5 presents the method to match pairs of points. A brief comparison with previous calibration methods is found in section 6. Here we show the problems associated with cameras using wide angle lens and why some previous methods fail or require a human operator. Experimental results are shown in Section 7. Finally, some conclusions are given in Section 8.

2. Computing Transformed Images

For integer coordinates \((i,j)\), let \(I(i,j)\) gives the intensity value of the pixel associated to position \((i,j)\) in image \(I\). Let \(I_d\) and \(I_t\) be the original (distorted image taken from the camera) and the transformed image, respectively. A geometric transformation, considering a set \(\Theta\) of parameters, computes pixels of the new image, \(I_t(i,j)\) in the following way:

\[
I_t(i,j) = I_d(x(\Theta,i,j),y(\Theta,i,j))
\]

(1)

If \(x(\Theta,i,j)\) and \(y(\Theta,i,j)\) are outside of the image \(I_0\), a common strategy is to assign zero value which represents a black pixel. But, What happen when \(x(\Theta,i,j)\) and \(y(\Theta,i,j)\) have real values instead of integer values? Remember that image \(I_d(x,y)\) have only valid values when \(x\) and \(y\) have integer values. An inaccurate method to solve this problem is to use their nearest integer values, but next section presents the bilinear interpolation, a much better method to interpolate a pixel with real coordinates \((x,y)\) in an image.

From other point of view, pixel \(I_d(x,y)\) moves to the position \(I_t(i,j)\). However, most transformations define points in the new image given points in the original image. In that case, to apply the bilinear transformation, we need to compute the inverse transformation that maps new points (or coordinates) to points (or coordinates) in the original image.

2.1 Bilinear Interpolation

If \(x\) and \(y\) are the integer and fractional part of \(x\), respectively, and \(x\) and \(y\) the integer and fractional part of \(y\), Figure 2 illustrates the bilinear interpolation method (Faugeras, 1993) to find \(I_t(x+x_f,y+y_f)\), given the four nearest pixels to position \((x+x_f,y+y_f)\): \(I(x,y), I(x+1,y), I(x,y+1), I(x+1,y+1)\) (image values at particular positions are represented by vertical bars in Figure 2). First two linear interpolations are used to compute two new values \(I(x,y+x_f)\) and

\[
I(x+x_f,y)
\]
I(x_i, y_i+yf) and then another linear interpolation is used to compute the desired value

\[ I(x_i+x_f, y_i+yf) \]

from the new computed values:

\[
\begin{align*}
I(x_i, y_i+yf) &= (1-y_f)I(x_i, y_i+y)I(x_i, y_i+1) \\
I(x_i+1, y_i+yf) &= (1-y_f)I(x_i+1, y_i+y)+y_fI(x_i+1, y_i+1) \\
I(x_i+x_f, y_i+yf) &= (1-x_f)I(x_i, y_i+y)+x_fI(x_i+1, y_i+y)
\end{align*}
\] (2)

Using the bilinear interpolation, a smooth transformed image is computed. Now we are able
to deal with the transformation associated with cameras. In section 5.3 we describe the
process to build new images from distorted images and the set of parameters of the
distortion and projection model.

Figure 2. Using the bilinear interpolation

3. The Distortion Model

The radial distortion process due to wide-angle lens is illustrated in Figure 3. Figure 3 (b)
shows an image taken from the camera when the pattern shown in Figure 3 (a) is in front of
the camera. Note the effect of lens, the image is distorted, specially in those parts far away
from the center of the image.

Figure 3. The distortion process due to wide angle lens
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Figure 3 (c) shows the radial distortion in detail, supposing that the center of distortion is the point $C_d$ with coordinates $(c_x, c_y)$ (not necessarily the center of the image). Let $I_d$ be the distorted image captured by the camera and $I_u$ the undistorted image associated to $I_d$. In order to correct the distorted image, the distorted point at position $P_d$ with coordinates $(x_d, y_d)$ in $I_d$ should move to point $P_u$ with coordinates $(x_u, y_u)$. Let $r_d$ and $r_u$ be the Euclidean distance between $P_d$ and $C_d$, and between $P_u$ and $C_d$, respectively. The relationship between radial distances $r_d$ and $r_u$ can be modeled in two ways:

$$r_d = r_u f_1(r_u^2)$$  \hspace{1cm} (3)

$$r_u = r_d f_2(r_d^2)$$  \hspace{1cm} (4)

Approximations to arbitrary function $f_1$ and $f_2$ may be given by a Taylor expansion:

$$f_1(r_u^2) = 1 + k_1 r_u^2 + k_2 r_u^4 + \ldots$$

and

$$f_2(r_d^2) = 1 + k_1 r_d^2 + k_2 r_d^4 + \ldots$$

Figure 4 helps to see the difference between $f_1$ and $f_2$ considering only $k_1$ for a typical distortion in a wide-angle lens. $f_1$ models a compression while $f_2$ models an expansion.

Figure 4. Two different functions to model the distortion of images.

The problem with $f_1$ is that there is the possibility to get the same $r_d$ for two different values of $r_u$ (see Fig. 5).

Figure 5. Problem using $f_1$. A single $r_d$ is related with two different $r_u$. 

In fact, this behavior was found experimentally when we use $f_1$. Figure 6 shows an example. Borders of the corrected image duplicate parts of the image (see the top corners in Figure 6(b)). However $f_2$ does not have this problem.

Figure 6. An example of a wrong correction using $f_1$

From now on, we consider only eq. 4. Experimentally we found that we need to consider four terms for $f_2$, to remove the distortion due to wide-angle lens. Then, the coordinates $(x_u, y_u)$ of $P_u$ can be computed by:

$$
x_u = c_x + (x_d - c_x)f_2(r_d^2)
$$

$$
y_u = c_y + (y_d - c_y)f_2(r_d^2)
$$

$$
r_d^2 = (x_d - c_x)^2 + (y_d - c_y)^2
$$

(5)

where $(c_x, c_y)$ are the coordinates of the center of radial distortion. So, this distortion model have a set of five parameters $\theta = \{c_x, c_y, k_1, k_2, k_3\}$. This model works fine if the camera have square pixel, but if not, we need another parameter, $s_x$, called aspect ratio that divide the term $(x_d - c_x)$. Since most cameras have square pixels, we consider $s_x = 1$.

Figure 7 helps to understand the process to transform the image taken from the camera, $I_d$, to a new image, $I_u$, similar to the reference image. A point $P_d$ in image $I_d$ with coordinates $(x_d, y_d)$ maps to an undistorted point $(x_u, y_u)$. Figure 7(b) illustrates the image without radial distortion and the transformation $T_u$ that maps the point with coordinates $(x_u, y_u)$ to new coordinates $(x_p, y_p)$. This new image is bigger than $I_u$ because the compression due to the wide angle lens has been removed, lines in the environment maps to lines in this image.

In a second step, the point with coordinates $(x_u, y_u)$ is projected to a new point $(x_p, y_p)$ in image $I_t$. Next section focuses in this projection step.

4. The Projection Model

Figure 3 shows and ideal case, where the plane of the pattern is parallel to the camera plane and center of the pattern coincides with the optical axis of the camera. A more realistic case is illustrated in Figure 7. Conceptually we can assume that a pinhole camera captures the undistorted image (a planar image) into the new image $I_t$. Since cameras are projective devices, a projective transformation is involved. A projective transformation is the most general transformation that maps lines into lines (Hartley & Zisserman, 2004).
Using homogeneous coordinates, the class of 2-D planar projective transformations between the camera plane and the plane of the undistorted image is given by (Szeliski, 1996) (Hartley & Zisserman, 2004) \[ \begin{bmatrix} x_p' \\ y_p' \\ w_p' \end{bmatrix} = M \begin{bmatrix} x_u' \\ y_u' \\ w_u' \end{bmatrix}, \]
where matrix \( M \) is called an homography and it has eight degrees of freedom. For our calibration application, \( M \) has the form:
\[
M = \begin{bmatrix}
m_0 & m_1 & m_2 \\
m_3 & m_4 & m_5 \\
m_6 & m_7 & 1 \\
\end{bmatrix}
\]
Plane and homogeneous coordinates are related by \((x_u'=x_u/w_u', y_u'=y_u/w_u')\) and \((x_p'=x_p/w_p', y_p'=y_p/w_p')\). So, a point \( P_u(x_u, y_u) \) in image \( I_u \) moves to \( P_p(x_p, y_p) \) in the new projected image \( I_t \).
Assigning \( w_u=1 \), the new coordinates of \( P_p \) are given by:
\[
\begin{align*}
x_p &= \frac{m_0x_u + m_1y_u + m_2}{m_3x_u + m_4y_u + m_5} + 1 \\
y_p &= \frac{m_3x_u + m_4y_u + m_5}{m_6x_u + m_7y_u + 1}
\end{align*}
\]  
(6)
And now the projection parameters are \( \Theta = \{m_0, m_1, m_3, m_4, m_5, m_6, m_7\} \).
5. The Point Correspondences Method

The goal is to find a set of parameters $\Theta$ that transform the distorted image captured by the camera, $I_d$, into a new projected image, $I_p$, that match the image, $I_r$, of the calibration pattern put in front of the camera. To do that, a set of point correspondences are extracted from $I_d$ and $I_r$ (see section 5.2 for details).

Let $n$ be the number of features, $(x_{rk}, y_{rk})$ be the coordinates of the $k$-th feature ($k=1,...,n$) in $I_r$ and $(x_{dk}, y_{dk})$ be its correspondence point in $I_d$. From $(x_{dk}, y_{dk})$ and using eq. 5, we can compute $(x_{uk}, y_{uk})$ and using eq. 6, we can get the coordinates $(x_{pk}, y_{pk})$ of the projected feature. So we have a set of pairs of points $C = \{((x_{r1}, y_{r1}), (x_{p1}, y_{p1})), \ldots, ((x_{rn}, y_{rn}), (x_{pn}, y_{pn}))\}$.

We formulate the goal of the calibration as to find a set of parameters $\Theta = \Theta^d \cup \Theta^p$ such the sum, $E$, of square distances between projected points and reference points is a minimum,

$$e_{xk} = y_p(\Theta, x_{rk}, y_{rk}) - y_{rk}$$
$$e_{yk} = y_p(\Theta, x_{rk}, y_{rk}) - y_{rk}$$
$$E(\Theta) = \sum_{k=1}^{n} (e_{xk}^2 + e_{yk}^2)$$

$$\Theta = \arg\min E(\Theta)$$

5.1 Non-Linear Optimization

The Gauss-Newton-Levenberg-Marquardt method (GNLM) (Press et al., 1986) is a non-linear iterative technique specifically designated for minimizing functions which has the form of sum of square functions, like $E$. At each iteration the increment of parameters, vector $\Delta \Theta$, is computed solving the following linear matrix equation:

$$[A + \lambda I] \Delta \Theta = B$$

If there is $n$ point correspondences and $q$ parameters in $\Theta$, $A$ is a matrix of dimension $q \times q$ and matrix $B$ has dimension $q \times 1$ and $\Delta \Theta = [\Delta \Theta_1, \Delta \Theta_2, \ldots, \Delta \Theta_q]^T$. $\lambda$ is a parameter which is allowed to vary at each iteration. After a little algebra, the elements of $A$ and $B$ can be computed using the following formulas,

$$a_{i,j} = \sum_{k=1}^{n} \left( \frac{\partial x_{rk}}{\partial \Theta_i} \frac{\partial y_{rk}}{\partial \Theta_j} + \frac{\partial y_{rk}}{\partial \Theta_i} \frac{\partial y_{rk}}{\partial \Theta_j} \right)$$
$$b_j = -\sum_{k=1}^{n} \left( \frac{\partial x_{rk}}{\partial \Theta_j} e_{xk} + \frac{\partial y_{rk}}{\partial \Theta_j} e_{yk} \right)$$

In order to simplify the notation, we use $x_{p}$ instead of $x_{rk}$ and $y_{p}$ instead of $y_{rk}$. Then, $\frac{\partial x_{p}}{\partial \Theta_j}$ and $\frac{\partial y_{p}}{\partial \Theta_j}$ for $(\Theta \in \Theta^p)$ can be derived from eq. 6.
\[
\frac{\partial x_p}{\partial m_0} = \frac{x_p}{D} \quad \frac{\partial y_p}{\partial m_0} = 0 \\
\frac{\partial x_p}{\partial m_1} = \frac{y_p}{D} \quad \frac{\partial y_p}{\partial m_1} = 0 \\
\frac{\partial x_p}{\partial m_2} = 1 \quad \frac{\partial y_p}{\partial m_2} = 0 \\
\frac{\partial x_p}{\partial m_3} = 0 \quad \frac{\partial y_p}{\partial m_3} = \frac{x_p}{D} \\
\frac{\partial x_p}{\partial m_4} = 0 \quad \frac{\partial y_p}{\partial m_4} = \frac{y_p}{D} \\
\frac{\partial x_p}{\partial m_5} = 0 \quad \frac{\partial y_p}{\partial m_5} = \frac{1}{D} \\
\frac{\partial x_p}{\partial m_6} = -x_p \frac{x_p}{D} \quad \frac{\partial y_p}{\partial m_6} = -y_p \frac{x_p}{D} \\
\frac{\partial x_p}{\partial m_7} = -y_p \frac{y_p}{D} \quad \frac{\partial y_p}{\partial m_7} = -y_p \frac{y_p}{D}
\]

Where \( D = m_6 x + m_7 y + 1 \). Partial derivatives of distortion parameters are derived from eq. 5 and two applications of the chain rule,

\[
\frac{\partial x_p}{\partial \theta_i} = \frac{\partial x_p}{\partial x_i} \frac{\partial x_i}{\partial \theta_i} + \frac{\partial x_p}{\partial y_i} \frac{\partial y_i}{\partial \theta_i} \quad \theta_i \in \{c, c, k_1, k_2, k_3\} \\
\frac{\partial y_p}{\partial \theta_i} = \frac{\partial y_p}{\partial x_i} \frac{\partial x_i}{\partial \theta_i} + \frac{\partial y_p}{\partial y_i} \frac{\partial y_i}{\partial \theta_i} \quad \theta_i \in \{c, c, k_1, k_2, k_3\}
\]
Correcting Radial Distortion of Cameras with Wide Angle Lens Using Point Correspondences

\[
\frac{\partial x_p}{\partial x_u} = \frac{D m_0 - (m_1 x_u + m_1 y_u + m_2) m_x}{D^2} \\
\frac{\partial y_p}{\partial x_u} = \frac{D m_1 - (m_1 x_u + m_2 y_u + m_3) m_x}{D^2} \\
\frac{\partial x_p}{\partial y_u} = \frac{D m_2 - (m_1 y_u + m_2 y_u + m_3) m_x}{D^2} \\
\frac{\partial y_p}{\partial y_u} = \frac{D m_3 - (m_1 x_u + m_1 y_u + m_2) m_x}{D^2}
\] (12)

Finally, the last set of formulas are derived from eq. 5,

\[
\frac{\partial x_u}{\partial k_1} = r^*_j (x_d - c_x) \\
\frac{\partial y_u}{\partial k_1} = r^*_j (y_d - c_y) \\
\frac{\partial x_u}{\partial k_2} = r^*_j (x_d - c_x) \\
\frac{\partial y_u}{\partial k_2} = r^*_j (y_d - c_y) \\
\frac{\partial x_u}{\partial k_3} = r^*_j (x_d - c_x) \\
\frac{\partial y_u}{\partial k_3} = r^*_j (y_d - c_y)
\] (13)

Where \( r_d \) was defined previously in eq. 5.
Next section describes how to compute feature points from each image, as well as their correspondences automatically.

5.2 Selecting Feature Points
As we can see in Figure 6(a), the image has white squares over a black background. As robust feature points we select the center of mass of each one of the white squares (or distorted white squares) of both images. The mass of each pixel is its gray level in the range [0-255] (0 for black pixels and 255 for white pixels).

In the implementation, once a white pixel is found (considering a given threshold), its cluster is identified visiting its neighbors recursively, and the center of mass is computed from all pixels in the cluster.

To compute automatically point correspondences, we assume that the array of white squares in each image is centered, specially in the case of the image from the camera. In this way, bad clusters (for instance when the camera capture some white areas outside of the calibration pattern) can be eliminated because the good clusters are closer to the image center. This is not a problem with the reference pattern, because we use the perfect graphic file of the image and there are no bad clusters of white pixels.

We also assume that the image from the camera does not have a significant rotation, relative to the reference image, so relative positions of white squares hold in both images. For instance, the top left-most white square is the closest square to the top-left corner of the image.

5.3 Computing Corrected Images
If we compute a set of parameters $\Theta$ we are able to map a point $(x, y)$ into a new projected point $(x_I, y_I)$. But to compute a new image $I_r$ we need the inverse mapping: to set the pixel value with integer coordinates $(x, y)$ in $I_r$ we need to compute the pixel value with coordinates $(x, y)$ in the distorted image $I_r$.

It is easy to compute $(x, y)$ given $(x_I, y_I)$ and the homography $M$. In homogeneous coordinates, $[x, y, w] = M [x', y', w]$. However, it is harder to compute $(x, y)$ given $(x_I, y_I)$. There is no a direct way to solve this problem. To solve it, we use the binary search algorithm. Our goal is to find $r_I$ given $r_2 = (x_I-c_2)^2+(y_I-c_2)^2$, $k_2$ and $k_0$. Once $r_I$ has been found, $x_I$ and $y_I$ are easily computed using eq. 5. $(x_I = (x_I-c_2) / f(r_I) + c_2$ and $y_I = (y_I-c_2) / f(r_I) + c_2$. From eq. 4, we formulate a new function $f$:

$$f(r_I) = r_I - r_Is(r_I) = r_I - r_I(1+k_2 r_2^2+k_3 r_2^4+k_5 r_2^6)$$

If $x_I=c_2$ and $y_I=c_2$ from eq. 5 we have $x_I=x_2$ and $y_I=y_2$. If $x_I\neq c_2$ and $y_I\neq c_2$ we need to find a low limit, $r_{il}$, and high limit, $r_{ih}$, such that $f(r_{il}) > 0$ and $f(r_{il}) < 0$. With these limits, the binary search algorithm is able to find the right $r_I$ such that $f(r_I)=0$ (or very close to zero) and then $r_I = r_I f(r_I)$. If $x_I\neq c_2$ and $y_I\neq c_2$ then $r_{ih}>0$ and $f(0)>0$, so we have the low limit $r_{il}=0$. To find the high limit $r_{ih}$, we iteratively increment $r_I$ until $f(r_I) < 0$. 


5.4 The Calibration Process

The calibration process starts with one image from the camera, \( I_a \), another image from the calibration pattern, \( I_b \), and initial values for parameters \( \Theta \). In the following algorithm, \( \Theta \) and \( \delta \Theta \) are considered as vectors. We start with \((c_a, c_b)\) at the center of the image, \( k_1= k_2= k_3=0 \) and the identity matrix for \( M \). The calibration algorithm is as follows:

1. From the reference image, compute the reference feature points \((x_k, y_k), (k=1..., n)\).
2. From \( \Theta \) and the distorted image, compute a corrected image.
3. From \((x_k, y_k), (k=1..., n)\) and \( \Theta \) compute \((x_{k}^*, y_{k}^*)\) \((k=1..., n)\).
4. From \((x_{k}^*, y_{k}^*)\) \((k=1..., n)\) and \( \Theta \) compute \((x_{k}^*, y_{k}^*)\) \((k=1..., n)\).
5. Find the best \( \Theta \) that minimize \( E \) using the GNLM algorithm:
   (a) Compute the total error, \( E(\Theta) \) (eq. 7).
   (b) Pick a modest value for \( \lambda \), say \( \lambda=0.001 \).
   (c) Solve the linear system of equations (8), and calculate \( E(\Theta+\delta \Theta) \).
   (d) If \( E(\Theta+\delta \Theta) \gg E(\Theta) \), increase \( \lambda \) by a factor of 10, and go to the previous step. If \( \lambda \) grows very large, it means that there is no way to improve the solution \( \Theta \).
   (e) If \( E(\Theta+\delta \Theta) < E(\Theta) \), decrease \( \lambda \) by a factor of 10, replace \( \Theta \) by \( \Theta+\delta \Theta \), and go to step 5a.
6. Repeat steps 2-5 until \( E(\Theta) \) does not decrease.

When \( \lambda=0 \), the GNLM method is a Gauss-Newton method, and when \( \lambda \) tends to infinity, \( \delta \Theta \) tends to zero. The calibration algorithm apply several times the GNLM algorithm to get better solutions. At the beginning, the clusters of the distorted image are not perfect squares and so point features can not match exactly the feature points computed using the reference image. Once a corrected image is ready, point features can be better estimated.

6. Related Approaches

There are two kinds of calibration methods. The first kind is the one that uses a calibration pattern or grid with features whose world coordinates are known. The second family of methods use geometric invariants of the image features like parallel lines, spheres, circles, etc. (Devernay & Faugeras, 2001).

The method described in this paper is in the first family of methods. Feature point correspondences are computed automatically. Some other methods require a human operator (with a lot of patience) to find such correspondences (Tamaki et al., 2001). Some other registration methods use all pixels of images as features, instead of a small set of point correspondences. However these methods need an initial set of parameters close enough to the right one and also have problems due to non uniform illumination (Tamaki et al., 2001).

The main problem when we have a high radial distortion is the accurate detection of features. Detect white clusters of pixels is easier than detect lines or corners. Some other methods apply the function \( f_6 \) of eq. (3), computing \( r_6 \) directly from \( r_5 \). But they tend to fail when there is a high radial distortion, as shown in Figure 6. Also, in order to correct images, we have to introduce more terms in the distortion model \((k_1,k_2,k_3)\). Other methods use only \( k_1 \) and find a direct solution for \( r_6 \). However they also fail to model higher radial distortions. Other methods (Ma et al. 2003) use a Taylor expansion of \( r_6 \) instead of \( k r_5^2 \). Experimentally we found better results using \( k r_6^2 \) instead of \( r_5 \) for wide angle lens.

Once a set of parameters was found using our method, computing each pixel of the new image is slow (due to the binary search method). However, in order to process many images...
from the same camera, that process of finding correspondences between $I_t$ (the new image) and $I_d$ (the distorted image) should be done only once. Given such correspondences, the bilinear interpolation process is very fast and a new corrected image is computed quickly.

We have described a calibration method based on the Gauss-Newton-Levenberg-Marquardt non-linear optimization method using analytical derivatives. Other approaches compute numerical derivatives (Devernay, 1995; Sten, 1997; Devernay 2001), so we have faster calculations and better convergence properties.

7. Experimental results

We test a MDCS2, 1/3” format CMOS, Firewire color camera from Videre Design with a 3.5mm C-mount lens. This camera acquire 15fps with resolution of 1280 x 960 pixels. The pattern calibration (image $I_r$), showed in Figure 8(a), was made using the program xfig under Linux. The image taken by the camera is shown in Figure 8(b). The corrected and projected image, using our point correspondences method, is shown in Figure 8(c), a very good result. The GNLM process was applied twice, requiring 6 iterations in the first case and 108 iterations in the second case. The error $E$ after the first GNLM search was $1.706 \times 10^5$ and at the end of the second search it was $1.572 \times 10^5$. It is interesting to compute the maximum individual distance between points $d_i = \sqrt{e_x^2 + e_y^2}$ to see the maximum individual error. Using this criteria, at the end of the process we got $d_{\text{max}} = 1.86$ pixels. The final parameters found are listed in Table 1.

![Figure 8. The calibration process](image-url)
Finally, Figure 9 shows an example of removing distortion using an image of our Laboratory.

Figure 9. Original and corrected images

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<th>m₀</th>
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<td>-.00002</td>
<td>-.000036</td>
</tr>
<tr>
<td>m₈</td>
<td>k₁</td>
<td>k₂</td>
<td>k₃</td>
<td>cₓ</td>
<td>cᵧ</td>
<td>sₓ</td>
<td></td>
</tr>
<tr>
<td>-.000048</td>
<td>1.2026E-6</td>
<td>-4.2812E-13</td>
<td>6.6317E-18</td>
<td>508.936</td>
<td>625.977</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Final set of parameters

8. Conclusions

We propose a robust method to remove radial distortion from images using a reference image as a guide. It is based on point correspondences between the acquired image from the
camera (with wide-angle lens) and the reference image. This method is faster than image registration methods and it is able to model high radial distortions. Also the selection of the center of mass of clusters of white pixels within images, as point features, are easier to detect than lines or corners. Another advantage of this method is its good convergence properties even starting with a set of parameters that no introduces any distortion.

This method was implemented in Linux and it is available online\(^1\), using the C language and standard routines from the Free Gnu Scientific library (GSL) to solve the linear system of equations and to find the inverse of matrix \(M\).

9. References


Ma, Lili; Chen, YangQuan & Moore, Kevin L. (2003), A new analytical radial distortion model for camera calibration.


\(^1\)http://faraday.fie.umich.mx/~lromero/calibrate.html
This book reports recent advances in the use of pattern recognition techniques for computer and robot vision. The sciences of pattern recognition and computational vision have been inextricably intertwined since their early days, some four decades ago with the emergence of fast digital computing. All computer vision techniques could be regarded as a form of pattern recognition, in the broadest sense of the term. Conversely, if one looks through the contents of a typical international pattern recognition conference proceedings, it appears that the large majority (perhaps 70-80%) of all pattern recognition papers are concerned with the analysis of images. In particular, these sciences overlap in areas of low level vision such as segmentation, edge detection and other kinds of feature extraction and region identification, which are the focus of this book.

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