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EFFICIENT PLANAR SELFCALIBRATION OF A STATIONARY CAMERA WITH VARIABLE INTRINSIC PARAMETERS

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ABSTRACT

In this paper, an unknown planar scene is used to auto-calibrate a camera with variable intrinsic parameters. The images are obtained by changing the zoom of the camera giving the calibration matrices different from one view to another. The principal idea of our method reside in the use three matches only between three images of the planar scene for computing the projection matrix of a parallelogram and the application to the camera a pure rotation giving other equations of self-calibration .The computing of the projection matrix in the i^{th} image leads us to establish a mathematical relationship between it and the image of the absolute conic in the same view. That is said, a non-linear cost function is formulated whose minimization allows us to estimate the parameters of the image of the absolute conic and consequently the elements of each calibration matrix can be determined from those of the image of the absolute conic. The experimental results show the effectiveness of our approach in terms of robustness, convergence and stability.

Keywords: *Auto-calibrate, variable intrinsic parameters, absolute conic, parallelogram, pure rotation.*

1. INTRODUCTION

In computer vision the camera plays a vital role what returns the determination of its internal parameters a challenge to raise. These can be estimated by two methods, calibration and autocalibration. The calibration method [1,2,3] is designed to calculate the parameters by the use an object 2D or 3D characterized by some 3D points known in the reference of the scene with its projections in the plans of images built a system of linear equations of which the resolution allows to calibrate the camera used, there are other methods of calibration that is directly use the image [4], but it must contain specific objects (parallelogram , cube, cuboid, ...) and the location of these objects in the image can also solve a system of linear equations to estimate the parameters of the camera or are based on new techniques [5] working on scenes unknown .

The autocalibration [6,7,8,9,10] in its turn consist to estimate the parameters of camera without any knowledge about the scene. The principle of this method is to search the equations in function of intrinsic parameters of cameras and invariants in images. Autocalibration equations are generally nonlinears and require two steps to solve: initialization and optimization of a non-linear cost function.

Our autocalibration technique is related to a camera with variable intrinsic parameters ,under a pure rotation, starting from an unknown planar scene.The main idea of our method moreover the previous point is the use only three matches (represents three vertices of a parallelogram) to determine the projection matrix of the parallelogram in each image and too a demonstration of the existance of a relationship between the projection matrix of parallelogram and the image of the absolute conic.

The strong characteristic of our approach reside in the three preceding points to formulate a non-linear cost function such as its minimization by Levenberg-Marquardt algorithm [12] provides the calibration matrix in each image . The figure 1 shows the autocalibration procedure by our method.

The present paper is organized as follows: the second section presents a passage in review of works published in this area, in the third section the pinhole model of the camera and the parameters of the parallelogram were presented then the

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projection of the parallelogram was treated . Our technique of autocalibration is described in the fifth part of this work, the following sction expose the experimental part and the last part presents a conclusion.

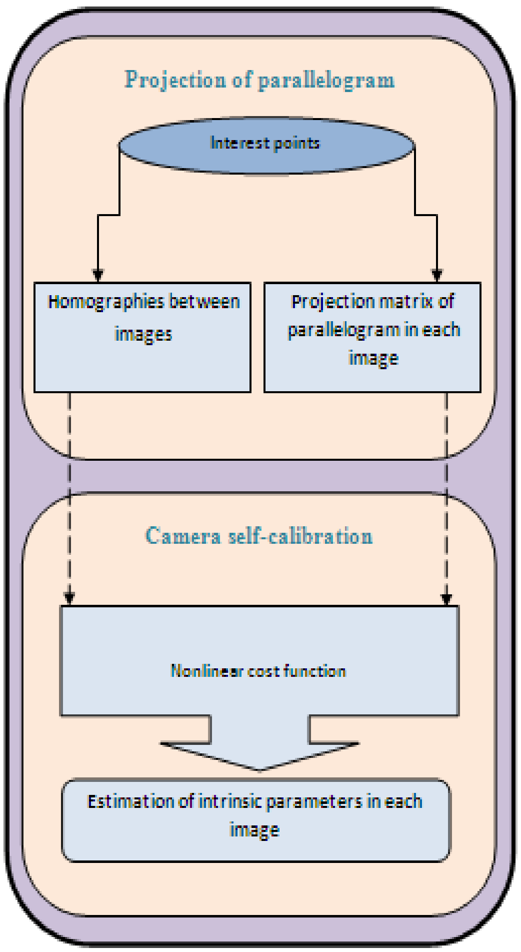

Figure 1: Procedure Of Our Self-Calibration Algorithm

2. SURVEY OF RELATED WORKS

In [18] the authors presented a practical algorithm to auto calibrate a camera with variable intrinsic parameters. They recovered the calibration matrix for each view by minimizing a system of nonlinear equations. The minimization procedure is started by a first initialization to give a first estimation of the focal distance thereafter the estimation of intrinsic parameters is performed by an algorithm in several iterations, in each iteration one parameter is estimated on the assumption constraints on other. In [19] the problem addressed is the self-calibration of a camera with variable focal length starting from the views of a unknown planar figure .The contribution is at several levels: Proposition of a new nonlinear formulation independent of the focal length, proposition of the exact solutions of which one can be obtained by linear estimation if the plan of the figure is a fronto-parallel plan (relatively with the key view). The performance of this algorithm is validated by experiments. This approach is dual to the usual method based on the properties of the images of the circular points. Indeed, the authors proposed a constraint which expresses the alignment of three points, one of which is the pole of the line at infinity compared to the image of the dual conic at the circular points.

In [20] a practical method of self-calibration of cameras with varying intrinsic parameters is proposed, this method can retrieve the metric reconstruction from a sequence of images, and the authors showed that the absence of skew alone is sufficient to calibrate the cameras used. In [21] the authors have considered the problem of self-calibration of a moving camera whose intrinsic parameters are known, except the focal length, which can vary freely between different views. The conditions, under which the determination of values of the focal length for a sequence of images is not possible, are derived. These depend only on the movements of the camera. They gave a complete catalog of sequences supposedly critical movements. It is then used to calculate the movement sequences for reviews stereo systems with variable focus.

In [22] the presented study describes a self-calibration algorithm using the camera with a small rotation around a single axis with fixed internal parameters but they are unknown the authors modified Triggs algorithm to incorporate factors scale and skew. The algorithm is applied to artificial objects whose size is known. The correctness of the algorithm is verified using synthetic data.

The problem addressed in [23] is that of self-calibration of cameras with varying intrinsic parameters from image sequences of an object, this method is based on a constant movement between images of the rotating object around a single axis, the relationship between the projection matrices and those of the fundamental matrices provides camera parameters by solving a system of non-linear equations. The problem addressed in [24] is self-calibration of cameras with varying intrinsic parameters, this method is based on the transformation of the image of the absolute dual quadric; this transformation is performed on all elements of the image of the absolute dual quadric

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to obtain the same magnitude for all these elements, which can make the solutions more stable. In [25], a method of self-calibration of cameras with varying intrinsic parameters, based on the quasi-affine reconstruction, after this reconstruction, the homography of the plane at infinity can be determined, and used with constraints on the image of the absolute conic to estimate the intrinsic parameters of cameras used.

A new method is presented in [26], the vanishing line is used to self-calibrate the cameras characterized by constant intrinsic parameters, the resolution of three linear equations obtained from the circles and their respective center determine the vanishing line. The theory of these lines and circular points allows estimating the camera parameters.

in [27], a new method of camera self-calibration is treated it is based on an unknown 3D scene to calibrate a camera characterized by constant intrinsic parameters. To estimate the homographies matrices of the plane at infinity between the pair of images, a non-linear cost function is formulated from a special motion of the camera: translation and small rotation and the resolution of a linear cost function allows to estimate the intrinsic parameters of the camera.

3. PARAMETERIZATION OF THE CAMERA AND PARALLELOGRAM

3.1 Parameterization Of The Camera

The projection of the scene in the images is described by a model called pinhole (see Figure 2):

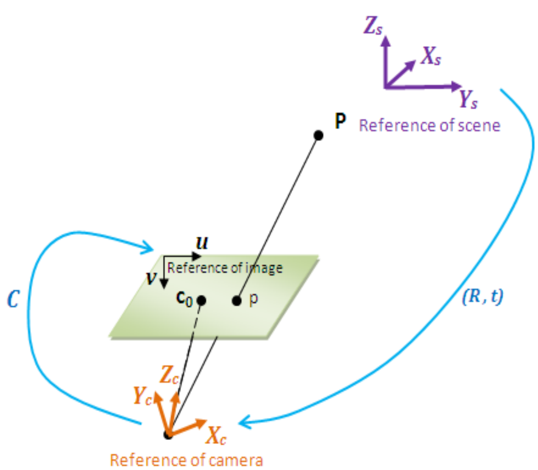

Figure 2: Pinhole Model Of Camera

With R the matrix of rotation, t the vector of translation , C is the calibration matrix , p is the projection of a scene point P and c_0 represent the principal point.

For an image i the passage of the scene reference to the camera reference is via the rotation R and the translation t, to pass the camera reference to image reference the matrix C must be determined. C is the calibration matrix, containing the intrinsic parameters of the camera, given by:

$$C_i = \begin{pmatrix} g_i & \tau_i & u_{i0} \\ 0 & \varepsilon g_i & v_{i0} \\ 0 & 0 & 1 \end{pmatrix} \quad (1)$$

g_i : the focal length
τ_i : the skew factor
ε_i : the scaling factor
u_{i0} and v_{i0} represents the coordinates of the principal point.

There are several camera models most commonly used is the so-called pinhole characterized by the projection matrix given by the following equation:

$$P_i = C_i (R_i \quad t_i) \quad (2)$$

3.2 Parameterization Of The Parallelogram

In this paper we are basead on a parallelogram to self-calibrate a camera. This object characterizes a natural geometric constraints frequently present in our environments such parallelism.

A parallelogram can be described by three parameters: two edge lengths and a angle between the edges (Figure 3).

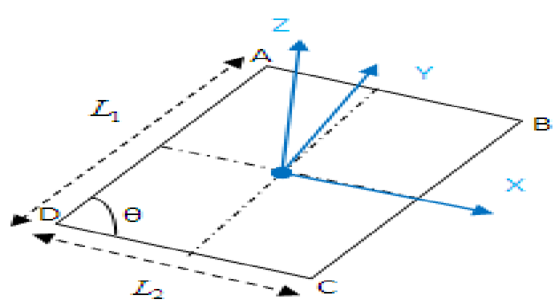

Figure 3: The Four Points Composing The Parallelogram

That being said, for each triplet of points A, B and C in the plane of the scene, there exists a unique point D such that ABCD is a parallelogram where the justification for using a such geometric entity in our Autocalibration camera.

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4. PROJECTION OF PARALLELOGRAM

The projection of the parallelogram can estimate all projection matrices in images using a few matches already determined, these matrices are exploited with homographies between images to estimate the intrinsic parameters of the camera. Homographies between the images of the scene are estimated by RANSAC function using the interest points determined by Harris and matched by the correlation function ZNCC.

4.1 Interest Points

Harris detector: To extract the local maxima of images of the scene, Harris [13,14,15] used the following matrix:

$$G = \begin{pmatrix} \left(\frac{\partial I}{\partial u}\right)^2 & \left(\frac{\partial I}{\partial u}\right)\left(\frac{\partial I}{\partial v}\right) \\ \left(\frac{\partial I}{\partial u}\right)\left(\frac{\partial I}{\partial v}\right) & \left(\frac{\partial I}{\partial v}\right)^2 \end{pmatrix} \quad (3)$$

For detecting the corners in images, Harris used a variable χ, which takes a value greater than zero in the case of a wedge, given by:

$$\chi = \det(G) - \zeta\, trace^2(G) \quad (4)$$

with $\zeta = 0.04$ value fixed by Harris.

4.2 Correlation Measure

The matching points of Harris previously detected is performed by using the correlation function [13,16,17] given by the following formula:

$$ZNCC(p_i, p_j) = \frac{\sum_n x_n y_n}{\sqrt{\sum_n x_n^2 \sum_n y_n^2}} \quad (5)$$

With p_i and p_j are two points of Harris detected in the images i and j and :

$$x_n = I(p_i + n) - \bar{I}(p_i)$$

$$y_n = I'(p_j + n) - \bar{I}'(p_j)$$

The point p_q ($q = i \text{ or } j$) is considered as the center of a $n \times n$ window set in the left and right image.

4.3 Projection Matrix Of The Parallelogram

Our parallelogram is linked to two references : affine (O, X_a, Y_a, Z_a) and Euclidean (O, X_e, Y_e, Z_e) its vertices and center (in the both references) are given by the following table:

Table 1: Center And Vertices Coordinates Of The Parallelogram

Affine plan		Euclidean plan	
Point	Coordinates	Point	Coordinates
A	$P_1^a = (-1, 1, 1)^T$	A	$P_1^e = (-s_1, s_3, 1)^T$
B	$P_2^a = (1, 1, 1)^T$	B	$P_2^e = (s_2, s_3, 1)^T$
C	$P_3^a = (1, -1, 1)^T$	C	$P_3^e = (s_1, -s_3, 1)^T$
D	$P_4^a = (-1, -1, 1)^T$	D	$P_4^e = (-s_2, -s_3, 1)^T$
O	$P_5^a = (0, 0, 1)^T$	O	$P_5^e = (0, 0, 1)^T$

Such as:

$s_1 = l_1 - l_2 \cos\theta$, $s_2 = l_1 + l_2 \cos\theta$, $s_3 = l_3 \sin\theta$,

$l_1 = \frac{L_1}{2}$ and $l_2 = \frac{L_2}{2}$.

The parallelogram ABCD expressed in the affine reference is projected in the image i by the matrix X_i following:

$$(u_{ir}\ v_{ir}\ 1)^T \cong X_i M_r \quad (6)$$

With $m_{ir} = (u_{ir}, v_{ir})^T$ is a point of the image i which represents the projection of a vertex or the center of the parallelogram, M_r is a vertex of the last entity (r = 1 to 3) and X_i is a 3x3 matrix which can be defined[11] by a factor near:

$$X_i \cong C_i R_i \begin{pmatrix} 1 & 0 & \\ 0 & 1 & R_i^T t_i \\ 0 & 0 & \end{pmatrix} J \quad (7)$$

R_i and t_i represents the position and orientation of the camera into the space and $J = \begin{pmatrix} l_1 & l_2\cos\theta & 0 \\ 0 & l_2 \sin\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}$ the transition matrix between the Euclidean and Affine references.

5. PROPOSED METHOD OF SELFCALIBRATION

Our approach of autocalibration is based on the use of the projection matrix of a parallelogram in each image and the relationship that we have implemented between these matrices and the image of the absolute conic. In order to have a system with more equations and consequently to ensure the determination of all the internal parameters of the camera, we applied to our camera a transformation consists of a pure rotation.

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5.1 Vision System

The scene is projected in the images by a camera with variable intrinsic parameters producing a pure rotation. The global reference system is placed in the optical center of the camera in its first position (Figure 4).

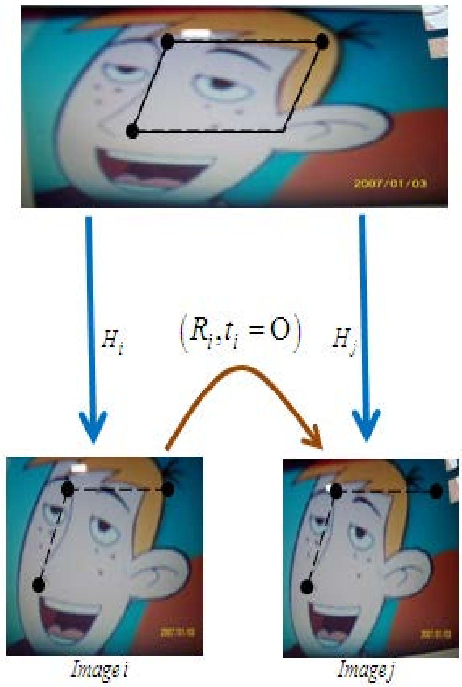

Figure 4: Projection Of Scene By Pinhole Model

With H_i and H_j are matrices of homographies for projecting the scene in the images i and j and R_i the rotation performed by the camera to get image j.

5.2 Equations Of Self Calibration

Our technique of autocalibration is based on the use of a parallelogram, the strong point of this choice is that it is always possible to obtain such a geometric object from any three points. Whether ABCD a parallelogram expressed in the affine plan and projected in the image i by a matrix X_i (see equations 6 and 7).

The matrix $H_i \approx C_i R_i \begin{pmatrix} 1 & 0 & \\ 0 & 1 & R_i^T t_i \\ 0 & 0 & \end{pmatrix}$ is the homography for projecting the plan of the scene in the image i, therefore the formula (7) becomes:

$$X_k \approx H_k J \tag{8}$$

With k equal to i for the image i and equal to j for the image j.

From equation (8) we deduce that:

$$X_j \approx H_{ij} X_i \tag{9}$$

With H_{ij} is the homography between the image i and j suchas:

$$H_{ij} = H_j H_i^{-1} \tag{10}$$

Developing the equation (7), we find that:

$$C_i^{-1} X_i \approx R_i \left(J' R_i^T t_i \right) \tag{11}$$

With $J' = \begin{pmatrix} l_1 & l_2 \cos\theta & \\ 0 & l_2 \sin\theta & \\ 0 & 0 & \end{pmatrix}$. The matrix R_i is orthogonal $(R_i^T R_i) = I$, So the relationship (11) can be written as follows:

$$X_i^T \omega_i X_i = \begin{pmatrix} J'^T J' & G'^T R_i^T t_i \\ t_i^T R_i J' & t_i^T t_i \end{pmatrix} \tag{12}$$

With $\omega_i = \left(C_i C_i^T \right)^{-1}$ is the image of the absolute conic.

For image j we will :

$$X_j^T \omega_j X_j = \begin{pmatrix} J'^T J' & J'^T R_j^T t_j \\ t_j^T R_j J' & t_j^T t_j \end{pmatrix} \tag{13}$$

Let us pose :

$$X_i^T \omega_i X_i = \begin{pmatrix} x_{1i} & x_{4i} & x_{5i} \\ x_{4i} & x_{2i} & x_{6i} \\ x_{5i} & x_{6i} & x_{3i} \end{pmatrix} \tag{14}$$

And:

$$X_j^T \omega_j X_j = \begin{pmatrix} x_{1j} & x_{4j} & x_{5j} \\ x_{4j} & x_{2j} & x_{6j} \\ x_{5j} & x_{6j} & x_{3j} \end{pmatrix} \tag{15}$$

Supposing that:

$$\delta_i = \begin{pmatrix} x_{1i} & x_{4i} \\ x_{4i} & x_{2i} \end{pmatrix} \tag{16}$$

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δ_i containing the first two rows and columns of the matrix $X_i^T \omega_i X_i$ so from (14) we have :

$$\delta_i = J'^T J' \tag{17}$$

For the two images *i* and *j* the relation (17) can be rewritten as:

$$\delta_i \cong \delta_j \tag{18}$$

From the previous equation we deduce the two nonlinear equations between image *i* and *j*:

$$\begin{cases} x_{1i}x_{4j} - x_{1j}x_{4i} = 0 \\ x_{1i}x_{2j} - x_{1j}x_{2i} = 0 \end{cases} \tag{19}$$

Our camera undergoes a pure rotation which allows us to write $t_i = (0,\ 0,\ 0)^T$ for image i and $t_j = (0,\ 0,\ 0)^T$ for image j .

Hence the two following expressions:

$$x_{3i} = x_{5i} = x_{6i} = 0 \tag{20}$$

$$x_{3j} = x_{5j} = x_{6j} = 0 \tag{21}$$

From (21), (22) and (23) we can deduce the following system:

$$\begin{cases} x_{1i}x_{4j} - x_{1j}x_{4i} = 0 \\ x_{1i}x_{2j} - x_{1j}x_{2i} = 0 \\ x_{3i} = 0 \\ x_{3i} = 0 \\ x_{5i} = 0 \\ x_{5j} = 0 \\ x_{6i} = 0 \\ x_{6j} = 0 \end{cases} \tag{22}$$

Internal parameters of our camera are variables therefore for two images i and j we have ten unknowns, or the system obtained above contains only eight equations, hence the need to use at least three images.

Minimization: Equations of system (22) are nonlinears therefore to resolve it we minimizes the cost function follows:

$$\min_{\omega_{i,j}} \sum_{j=i+1}^{n} \sum_{i=1}^{n-1} \left(\alpha_{ij}^2 + \beta_{ij}^2 + \phi_i^2 + \varphi_j^2 + \gamma_i^2 + \sigma_j^2 + \Psi_i^2 + \rho_j^2\right) \tag{23}$$

With $\omega_{i,j} = \left(\omega_i \ \omega_j\right)^T$, n is the number of images used and :

$$\alpha_{ij} = x_{1i}x_{4j} - x_{1j}x_{4i}$$
$$\beta_{ij} = x_{2j}x_{1i} - x_{1j}x_{2i}$$
$$\phi_i = x_{3i},\ \varphi_j = x_{3j}$$
$$\gamma_i = x_{5i}$$
$$\sigma_j = x_{5j}$$
$$\Psi_i = x_{6i} \text{ and } \rho_j = x_{6j}$$

The minimization of (23) is given by Levemberg Marquardt algorithm [12].

Initialization : The elements of the matrix ω_λ ($\lambda = i, j$) must be initialized before minimization. Suppose that the following conditions are true:

The principal point is in the center of the image therefore $\mu_{0\lambda}$ and $v_{0\lambda}$ are known.

The pixels are square so $\varepsilon_\lambda = 1$.

By substitution these parameters in the system (22) we can estimate the focal lenghts g_i and g_j .

5.3 Determination of X_i and X_j

We have $X_i \cong H_i J$ for image i and $X_j \cong H_j J$ for image j (see formula 8) so:

$$X_j \cong H_{ij} X_i \tag{24}$$

With $H_{ij} = H_j H_i^{-1}$ is the homography between image i and image j . The projection of the vertices A, B and C in the two images is given by $\left(u_{ih}\ v_{ih} 1\right)^T \cong X_i M_h$ and $\left(u_{jh}\ v_{jh} 1\right)^T \cong X_j M_h$ with $1 \le h \le 3$ hence:

$$\left(u_{jh}\ v_{jh} 1\right)^T \cong H_{ij} X_i M_h \tag{25}$$

From equation (25) and $\left(u_{ih}\ v_{ih} 1\right)^T \cong X_i M_h$ and using the singular value decomposition we can determinate X_i . By using (24) we can also obtained X_j .

5.4 Self-Calibration Algorithm

Our selfcalibration method can be presented in the form of following stages:

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Stage1. Determination of interest points in each image by using de Harris detector.

Stage2. Matching of interest points by using de ZNCC algorithm.

Stage3. Estimating the matrices of homographies between images by using RANSAC algorithm.

Stage4. Estimating the projection matrix of parallelogram in each view.

Stage5. Formulating and minimizing of a non-linear cost function to obtain the intrinsic parameters in each image.

6. EXPERIMENTATION

6.1 Simulation

We simulate a sequence of 512x512 images of an unknown planar scene . To test the effectiveness of our method, we carried out a comparison with a classical method of calibration which is based on the use of a known calibration object and from a resolution of a system of equations, the intrinsic parameters can be determined in each image, the following table shows the results obtained.

Table 2: Results Obtained By A Classical Method Of Calibration

cameras	focal length	u_0	v_0	ε
Camera1	1792	257	262	0.91
Camera2	1788	259	264	0.95
Camera3	1796	258	261	0.97

The scene is projected into the images that are disturbed by white Gaussian noise with standard deviation σ (in pixels). Interest points are detected by Harris and matched by the correlation function ZNCC, then homographies between images and projection matrices of a parallelogram in all images are calculated, finally minimizing the non-linear cost function given by (23) permit to estimate the elements of image of the absolute conic and calculate the intrinsic parameters of the camera in each view.

The figure 5 and figure 6 shows the relative error on the focal length according to number of images and the noise applied to the images. The experiments shows that the error on the focal length decreases linearly when the number of images is greater than 3 (Figure 5) and it increases linearly with the noise (Figure 6) .

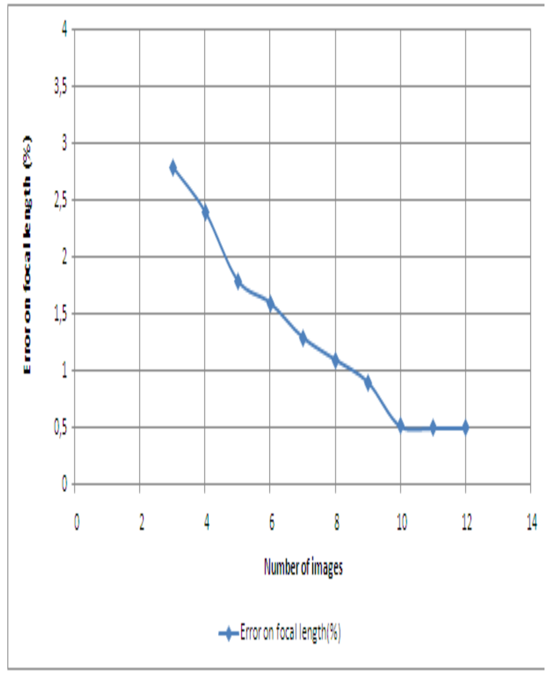

Figure 5: Error On Focal Length According To The Number Of Images

The figure above shows that our method converges from the tenth images. In fact the error on the focal length becomes constant once the number of the images is higher than ten.

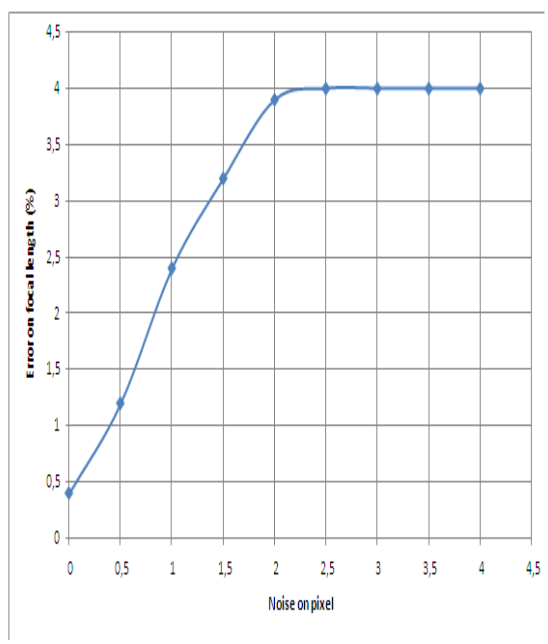

Figure 6: Error On Focal Length According To The Noise

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The noise applied to the images becomes useless as soon as the standard deviation exceed the value 2 which explains the robustness of our approach.

6.2 Real Data

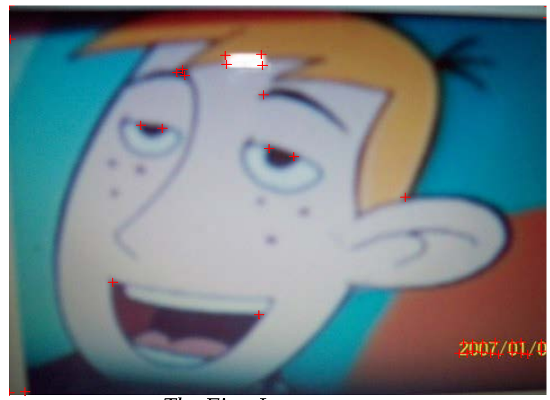
To show the robustness of our method , three images of size 512 × 512 of a unknown planar scene are acquired by a digital camera with variable intrinsic parameters (Figure 7).

Figure 7: The Three Images Used

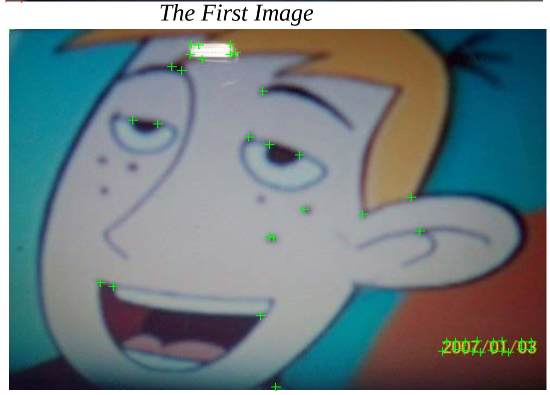
The homographies between the images and the projection matrices of a parallelogram in all the images are calculated and finally the resolution of the system of non-linear equations (22) to estimate the elements of image of the absolute conic and calculate the intrinsic parameters of the camera in each view.

6.2.1 Detection of interest points

The interest points in the three images are detected by using the Harris's detector [13,14,15] (Figure 8).



The First Image



The Second Image

The Third Image

Figure 8: Corners Detected By Harris Detector

6.2.2 Matching of interest points

The matching points detected in the previous phase between the first pair of images (image 1 and image2) and the second pair (image 1 and image3) is given by the algorithm ZNCC [13,16,17] (Figure 9).

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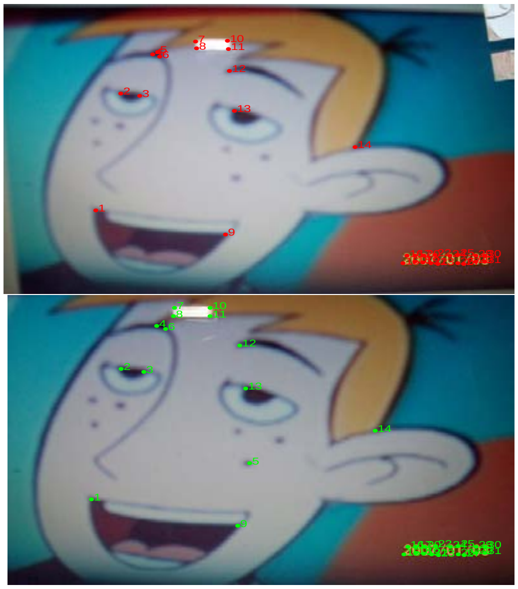
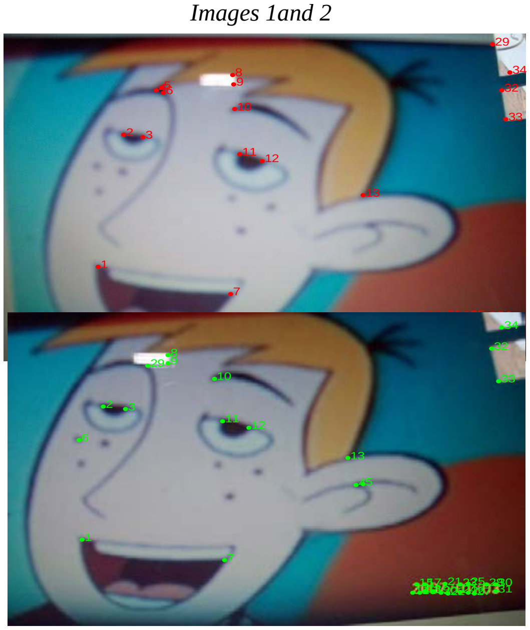


Images 1and 2



Images 1and 3

Figure 9: Matching Of Interest Points By ZNCC

6.2.3 Estimation of the intrinsic parameters

To estimate the intrinsic parameters of each camera by our approach two phases must be implemented initialization to provide a initial solution and the minimization of cost function (23) to find an optimal solution (Table 3).

Table 3: Results Obtained By Our Self-Calibration Algorithm

Cameras	Focal length	u_0	v_0	ε
Initial solution				
Camera1	1735	256	256	1
Camera 2	1737	256	256	1
Camera 3	1741	256	256	1
Optimal solution				
Camera 1	1795	260	265	0,93
Camera 2	1799	259	261	0,94
Camera 3	1792	263	267	0,97

The table above shows the results obtained by our technique described in this present article. In fact it contains the initial solution obtained by substituting the parameters initialized in the system (22), this solution is necessary because it represents a input data to find the optimal solution by minimizing the non-linear cost function given by (23).

7. CONCLUSION

In the present work we have proposed a method of self-calibration of a CCD camera, with variable intrinsic parameters, performing a pure rotation and using a planar scene. The resulting system consists of sixteen equations ,or the number of unknowns in the real case is equal to fifteen (three images each image gives five parameters) where the possibility of considering all the internal parameters of the camera as variables which explains the performance and effectiveness of our method. The results show the robustness, convergence and stability of our technique.

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