WHEN SHOULD THE NON LINEAR CAMERA CALIBRATION BE CONSIDERED?

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Abstract: In 3D modelling reconstruction of points, lines, planes or conics are done in the virtual 3D space. Their situations in the 3D virtual scene are defined by the situation of the recognized features in one or several images. Estimation of a parameter vector which models the object is carried out starting with recognized features in the image. Since positions of recognized features in the image are contaminated with noise the solution for the parameter vector is not exact. In order to obtain "the best" solution, optimization algorithms which reduce a residual error are used. They can be classified into linear and non linear ones.The aim of this paper is to determine the quality of estimated parameters if no linear estimation process is utilized. It is shown that in some cases non linear optimization algorithms diverges and worst parameters are computed using non linear methods. In order to obtain experimental results, camera parameters have been estimated under different conditions.

1 INTRODUCTION

Computer vision is a branch of artificial intelligence and image processing concerned with computer processing of images from the real world. Computer vision typically requires a combination of low level image processing to enhance the image quality (e.g. remove noise, increase contrast) and higher level pattern recognition and image understanding to recognise features present in the image. In cases of 3D modelling, reconstruction of points, lines, planes or conics are done in the virtual 3D space. Their situations in the 3D virtual scene are defined by the situation of the recognized features in one or several images. In this category, equations that relate the parameters to be estimated with the coordinates of the features in the images are established. Therefore, estimation of the parameter vector is carried out starting with recognized features in the image. Since positions of recognized features in the image are contaminated with noise the solution for the parameter vector is not exact. In order to obtain "the best" solution, optimization algorithms are used. Optimization algorithms can be classified into linear or non linear one.

Linear algorithms provides a close form solution for "the best" parameter vector which fits with a given set of recognized features in the image. The parameter set can be computed by solving linear equations. Since no iterations are required, the solution is computed faster. However, such methods have two disadvantages. First, if non linear relation exists between image features and parameters, they can not be computed and second, if the parameters satisfy some restriction, it is not guaranteed than the computed ones succeed it.

Non linear optimization methods involve using an iterative algorithm with the objective of minimizing residual errors of some index. The advantage of this type of technique is that the parameter estimation can cover non linear relation between the feature positions in the image and the parameters. Another advantage is that the algorithm may achieve high accuracy, provided that the estimation model is good, and correct convergence has been reached. However, since the algorithm is iterative, the procedure may end up with a bad solution unless a good initial guess is available. Furthermore, non linear relation included in the parameter space may result in a unstable minimization if the procedure of iterations is not properly designed. The iteration can lead to divergence or false solutions.

Two step optimization methods seem to be most useful. Parameters which accomplish linear relation are computed first with a close form solution and afterwards, they a used as initial guess to improve

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them and estimate the remaining parameters. Iterative schemes also use one set of parameters to estimate a second set of parameters which improves the first one. This is done iteratively until a threshold value of the residual error is achieved. The advantage of this method is that a closed form solution is derived for most for parameters and the number of parameters to be estimated through iterations is relatively small.
In this paper, an evaluation of the non linear parameter estimation method is carried out in order to define the conditions in which it works right. First, a small presentation of camera calibration method using a 3D pattern is done. Depending on the index to minimize the solution can differ. Second, an evaluation of different kinds of residual error is carried out. All this errors are combined in different situations and an estimation of the evolution of the non linear estimation algorithm is done. It is shown that in some situations the non linear estimation algorithm diverges and false solutions can be computed. Finally, experimental results are shown. In this case the camera parameters are estimated. Experimental results back what it has been presented in the paper.

2 NON LINEAR CAMERA CALIBRATION

Camera calibration process estimates the relation between the points coordinates in the pattern and its correspondence in the image. This relation is defined with the camera features and its localization in the scene. A linear relation exists if camera distortion is not considered. It is expressed with the following expression

$$f(m_{11},\dots,m_{34}) = \begin{bmatrix} u_i \\ v_i \end{bmatrix} = \begin{bmatrix} \dfrac{m_{11}x_i + m_{12}y_i + m_{13}z_i + m_{14}}{m_{31}x_i + m_{32}y_i + m_{33}z_i + m_{34}} \\ \dfrac{m_{21}x_i + m_{22}y_i + m_{23}z_i + m_{24}}{m_{31}x_i + m_{32}y_i + m_{33}z_i + m_{34}} \end{bmatrix}$$

$q_i=(u_i,v_i)$ are the points coordinates in the image, $p_i=(x_i,y_i, z_i)$ are its correspondences in the pattern and m_{ij} are the elements of the projection matrix M. The projection matrix is formed with the camera features and its location in the world (Faugeras 1993). The aim is to compute M starting with the points coordinates. Several methods exist (Hartley 2000)(Heikkilä 1997). First a linear estimation of camera parameters is carried out and after a non linear adjustment is done. Non linear adjustment is done including non liner relation of point's coordinates (Faugeras 1993). Since points coordinates are corrupted with noise, no exact solution will be achieve. The computed solution is the best one which satisfies given data. In the following the noisy data will be denoted with *q'* and *p'*.

2.1 Geometrical error

For an estimated projection matrix M^* a geometrical error e can be defined. This geometrical error is the sum of the Euclidean distance between the measured coordinate's *q'* of the points in the image and the result of projecting the 3D pattern *p'* in the image with the estimated matrix M^*. In this case q^* denotes the optimal image coordinates of the measured points, according to the estimated camera parameters.

$$e=\sum|q_i'-M^*p'_i|=\sum|q_i'-q^*_i|$$

Depending on the method utilized to compute the projection matrix M^*, the accuracy of the estimated parameters with the given data is better. In the following section a classification of linear and non linear method is done according to this geometrical error.

3 WHEN DOES THE NON LINEAR CAMERA CALIBRATION BE CONSIDERED?

Until now, all the effort goes to improve the estimation of the camera model parameters. This improvement is based in the minimization of the Euclidean distance between the measured points' coordinates *q'* and the ones q^* computed from an estimation of the camera parameters M^*. Starting parameters have been computed with linear methods which compute them using a close form solution. From an algebraic point of view, the result is correct but geometrically it could be absurd, since this error has no physical meaning. Parameters from the closed form solution are improved to obtain best fitting parameters which reduce the geometrical error. This means that the non linear estimation obtains a set of parameters with less geometrical error that those obtained with linear methods. This geometrical error is always regarding to the noisy measure of the points coordinates *q'* and *p'*. In fact, there is a set of noisy points used to accomplish the estimation process *q'* and *p'*, and there is another set of ideal points without noise *q* and *p* which are always unknown. In theory, if this set of ideal point's *q* and *p* were used in the estimation process, exact values of the model parameters will be

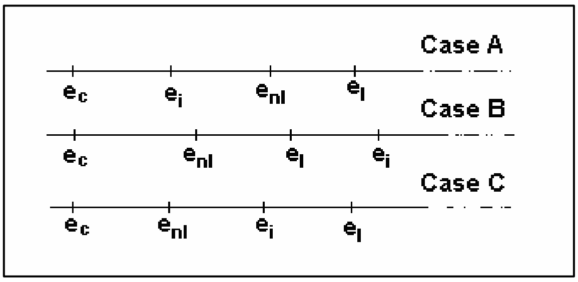

Figure 1: Estimation methods arranged in a line, based on their residual geometrical errors

computed. Due to the noise in the measured points coordinates, these ideal points are always unknown. That is why it is impossible to obtain the exact camera model parameters in any case.

If the estimated parameters are arranged in a line according to the geometrical error they generate, several situations arise. The residual geometrical error of the noise points with respect to themselves is always cero $e_c=0$. The geometrical error of the ideal points q and p regarding to the noisy points q' and p' is always an unknown value called e_i. Additionally, there are geometrical errors with the set of points generated with the parameters estimated with linear methods and the parameters estimated with non linear methods. These are called e_l, e_{nl} respectively. These errors are always known and they will be bigger than the geometrical error cero e_c. Moreover, since the set of points resulting from the non linear estimation has less geometrical error, e_{nl} will be always on the left side of e_l. Now, the essential question is, where is the unknown e_i?. The situation of this unknown, give us the efficiency of the non linear estimation regarding the linear one. If the exact parameters are those which generate a set of points with a geometrical error e_i, the goal is to compute a set of parameters which generate a set of points with a geometrical error close to the unknown e_i. Several situations showed in figure 1 arise.

In case A, better parameters will be always obtained using non linear estimation. In this case, since e_i is on the left side of e_{nl}, with the non linear estimation better results will be obtained. In the case B, since e_i is on the right side of e_l, with the non linear finding worse camera parameters will be computed. In the case C, the value of e_i is between e_{nl} and e_l. In this case, better results with the non linear method will be obtained if e_{nl} is closer to e_i. Since it is impossible to know the ideal points and therefore e_i, it is impossible to know if better results will be obtained with the non linear method.

However, although it is impossible to know the set of ideal points which give e_i, it is possible to know the noise level of the point's coordinates. This noise level gives the separation between e_i and e_c. If the noise level is elevated, e_i will be far from e_c. Otherwise, if the noise level is small, these values will be closer. In the case of elevated level of noise, the probability of obtaining a geometric error e_l situated is case B is very high since e_i and e_c are much separated. The set of parameters computed with the non linear method generates points which are closer of the noisy points. This means that the estimation is worse although the residual geometrical error is smaller. Therefore, with elevated noise level it is more probably to obtain worse results if the non linear method is used. From the finding algorithm point of view, if the noise level is high, the starting values of the parameters are far from the ideal ones. This means that the finding algorithm is unable to achieve the absolute minimum and it is deviated to local one. This local minimum gives worse values of the parameters although the geometrical error is small. Otherwise if the noise level is small, e_i is closer to e_c. Consequently, the probability of e_l is higher in the case A. In this case the parameters computed with the non linear method are better. The finding algorithm reduces the geometrical error and it is closer to the ideal one. Since the starting values of the parameters are close to the ideal one, the finding algorithm stops close to the absolute minimum.

The question now is how do we decide if use or not non linear parameter estimation? The decision should be based on the noise level of the measurements of the points coordinates. Taking into account that most of geometric computation problems are χ^2 variables with r degrees of freedom, where r depends on the application, it is possible to know the noise level of the features coordinates. This noise level ε^2 is computed knowing the residual of the optimization. It is defined as

$$\varepsilon^2 = \frac{I^*}{r}$$

where I^* is the residual of the optimization (Kanatani 1995). It is necessary also to define the limit of noise level for which the non linear estimation deviates form the right solution. It should be done testing each application. In this paper camera calibration process has been tested.

In order to obtain better results, a new set of point's coordinates should be computed. If the measured point's coordinates are corrupted with noise and the finding algorithm tries to satisfy it, worse results will be obtained. Therefore, if a new set of point's coordinates with smaller level of noise is satisfied, better results will be obtained.

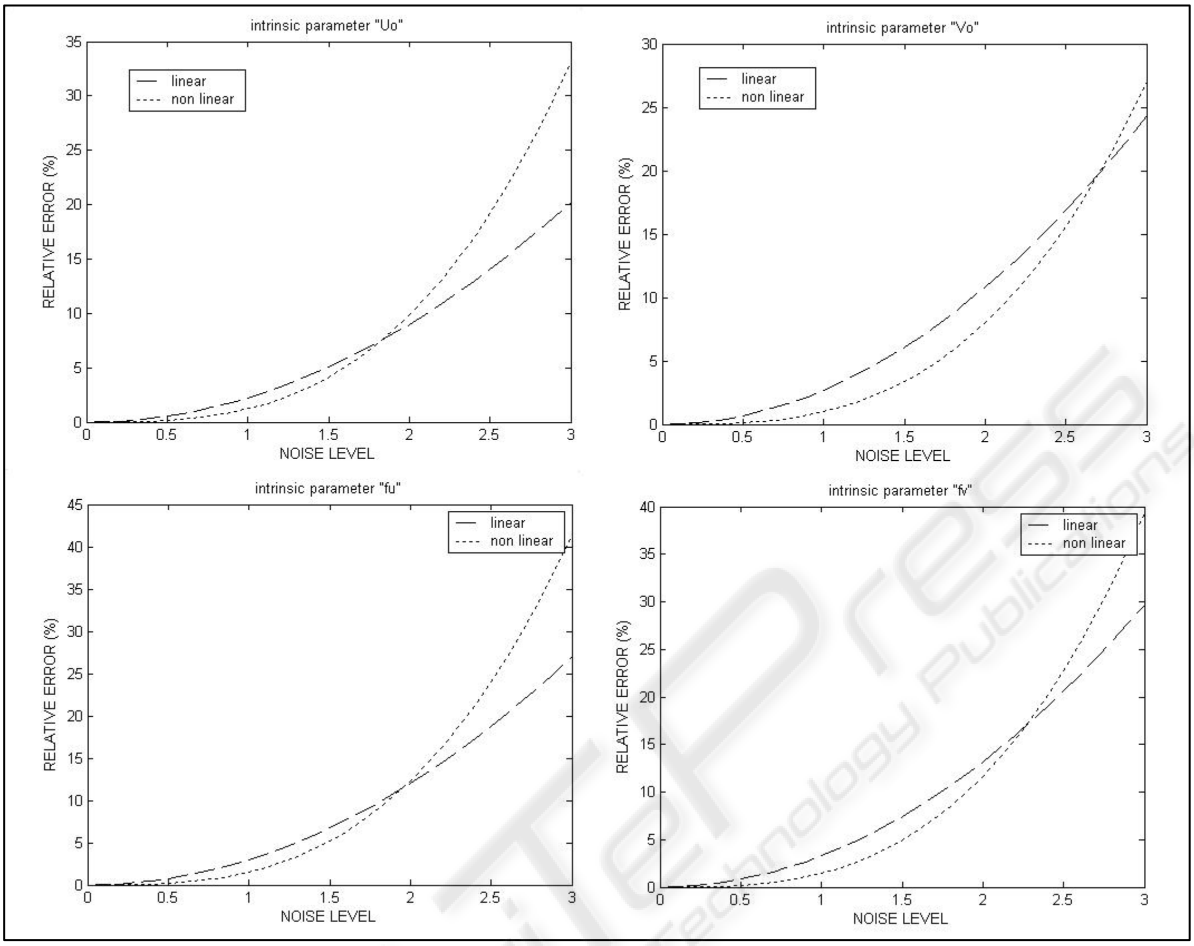

Figure 2: Relative error of estimated internal camera parameters

4 EXPERIMENTAL RESULTS

Both, simulated and real experiments have been done to test the performance of the optimization algorithms. First, calibration process with non linear algorithms is tested with synthetic data to extract conclusions about the influence of the noise level in the computed parameters. Second, the overall procedure is tested with real data provided with the images o calibration template. This second series of experiments demonstrates the validity of the overall deduction.

4.1 Simulated experiments with synthetic data

Several situations have been simulated in order to extract some conclusion about non linear calibration technique. A lot of different number of points of interest has been used. This feature has no significant effect on the estimated results from the point of view of deviation of the non linear parameters estimation. Finally, a set of 50 points in the scene arranged into two planes has been used. The camera is situated 1 m away form the Y axis, with an angle of incidence of the camera optical axe of 45 degrees with the X-Y plane. The starting values of the parameters are computed with the Direct Linear Transformation (DLT) algorithm (Hartley 2000). A priori, no camera intrinsic parameters are known. The non linear cost function is not critical in order to test the deviation of the non linear optimization. Similar results have been computed. Depending on the used cost function, one restriction or another is satisfied. Cost functions which include the restriction of the camera projection matrix have similar behaviour. The noise level in the point's coordinates is the only feature which has a lot of effect in the estimated camera parameters. The results are shown in figure 2. In this experiment the noise level changes from 0 to 3 pixels in the image coordinate points and from 0 to 3

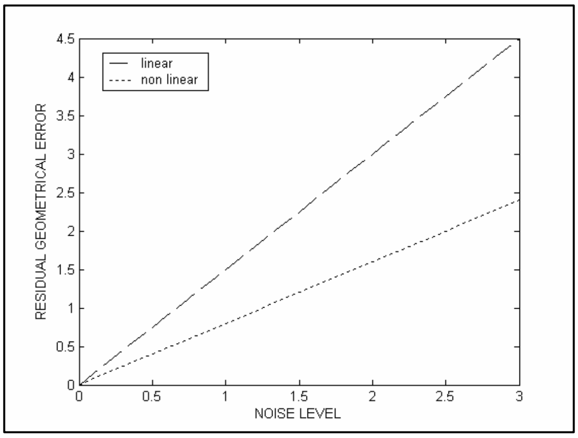

Figure 3: Residual geometrical error with linear and non linear method

mm in the 3D scene coordinate points. Steps of 0.1 have been taken. A set of points in the 3D scene arranged into two planes is used and a camera ideal model is generated with a set of intrinsic and extrinsic parameters. This ideal model is represented in a projection matrix which is used to calculate the projections in the image of the 3D points in the scene. Both sets of point's coordinates (image and scene) are corrupted with Gaussian noise. This corrupted data is used to compute the camera parameters, starting with the linear method and finishing with the non linear one. This process is done 100 times per step. After 100 times, the mean of the estimated parameters with the linear method and the non linear one are computed. Figure 2 shows the result for each level of noise. It shows the relative error for each value of the camera parameters. The continuous line shows the linear estimation and the dotted line is the non linear one. In this case, non linear estimation is done without any restriction included into the index. Results show that, non linear calibration method can not improve the results of the linear one, if the noise level is too high. This result demonstrates the bad performance of the non linear camera calibration method if the noise level is high.

The term "to improve the results" should not be interpreted as to reduce the geometrical error. It is true that the non linear camera calibration method reduces the geometrical error but from a practical point of view, this method computes worse values of the absolute camera model parameters. Figure 3 shows the residual optimization using linear and non linear optimization method. It is clear that the non linear optimization method reduces the geometrical error a lot, but when the noise level is high, this reduction does not improve the absolute values of the parameters.

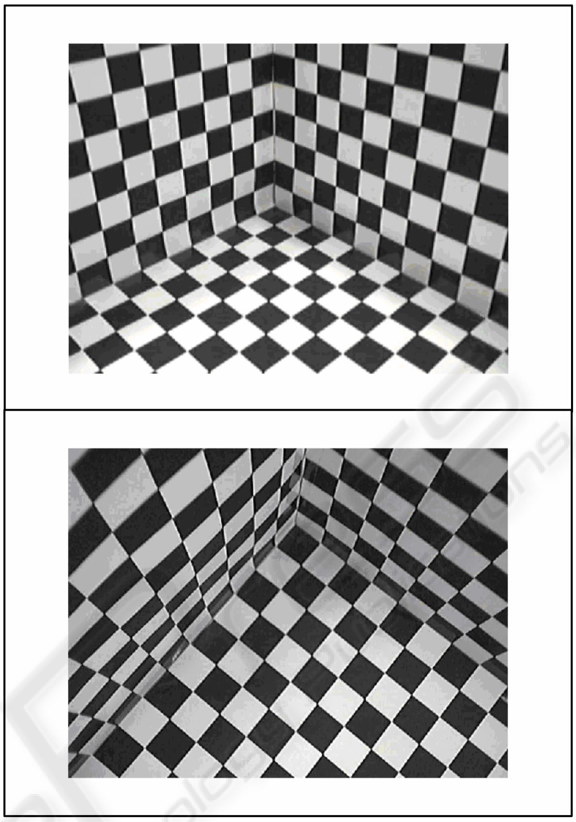

Figure 4: Images of the calibration template

Seeing the figures, the noise level from which the non linear optimization method computes worst results is about 2.1.

4.2 Experiments with real images

From the point of view of calibration of a real camera, images from different positions are taken of a calibration template. Calibration images are shown in figure 4. Images from different positions are taken to detect the coordinates of the calibration points with different accuracy. Then, the noise level of points coordinates changes. With these points, the calibration process has been carried out in the same way as in the simulation stage. Camera has been calibrated 100 times in order to extract mean values. Smaller residual optimization has been computed with non linear optimization techniques. Also, different parameters have been computed with each method. Since the real values of camera parameters are not known it is impossible to decide which calibration is better. However, the noise level of the points coordinates computed with the χ^2 test can help us to decide. In this case noise level about 2 has been computed with images 2 and 3 as is shown in table 1. Taking into account the simulated results, no linear optimization method should be discarded or better detection of the points coordinates in the image should be done. In this case, better calibration stage should be used.

Table 1: Results of experiments with real data

	Residual optimization		Noise level ε^2
	Lineal	Non linear	
Image 1	2.901	1.588	1.224
Image 2	5.687	1.026	2.345

These results can be extrapolated to any parameter estimation process. It is necessary to take into account the noise level of the input data before using non linear optimization techniques.

5 CONCLUSIONS

For parameters estimation, the non linear optimization method can be useful if the noise level of the input data is not very high. If the noise level is too high, the non linear optimization technique computes worst absolute results. The algorithm converges to a local minimum which improve the geometrical error but not absolute values of the parameters, even using the Levenberg-Marquardt finding algorithm. Non linear optimization minimizes a cost function with a lot of degrees of freedom and it can diverge to false results if the noise level is very high. In these cases linear parameter estimation methods are faster and achieve better results. In order to improve parameter estimation process using non linear techniques, low noise input data should be used.

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