Sub-pixel straight lines detection for measuring through machine vision

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***Abstract*—External visual interfaces for high precision measuring devices are based on the segmentation of images of their measuring reticle. In this paper, a method for subpixel straight lines detection is presented and tested on images taken from the reticle of a dark field autocollimator. The method has three steps, the sharpening of the image using a version of the Savitzky-Golay filter for smoothing and differentiation, the construction of a coarse edge image using Sobel filters, and finally, the subpixel edge location determination, by fitting a Gaussian function to orthogonal sections of the coarse edge image. We discuss results of applying the proposed method to images of the reticle of a Nikon 6D autocollimator, using the scale of the device as a benchmark for testing the error in the location of the lines and compare them with Sobel/Hough and Sobel/polynomial fitting. We report that for this type of image-content, Gaussian fitting has smaller uncertainty, when cameras with two different sensors are used.**

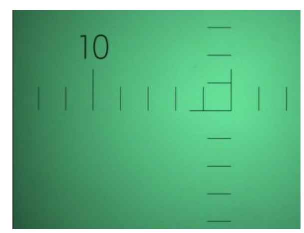
I. Introduction

Boundaries, physical contours, and general edge structure characterize objects in images. Locating edge structure fast and accurately is a main task of image processing and vision measuring. Modeling the image as a sample of a graph surface over a regular grid, edges can be detected using discrete gradient operators. Sobel, Prewitt and Canny edge detectors belong to this class of methods which search for abrupt changes in the image's intensity matrix, [1], [2]. These traditional methods treat pixels as an indivisible part of the image and perform edge detection with accuracy limited by the CCD's digital raster.

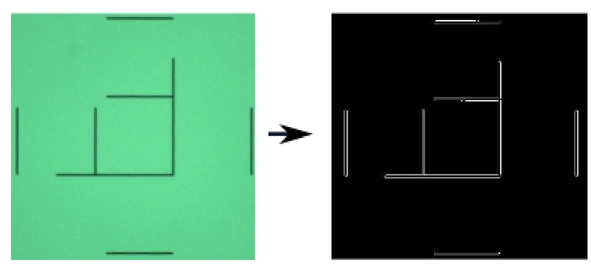
Industrial applications concerned with measuring of objects with high precision require the detection of edges and boundaries with sub-pixel accuracy [3]. To this purpose, edge binary outputs must be further processed to attain higher precision in the edge position. Methods introduced here are designed for straight line segmentations, such as box-sizes calculations [4], sports video frames calibration and synchronization, among others. Subpixel increasing resolution has also been introduced in industrial applications as glass width estimation [5], and high temperature specimen contour estimation [6], among others.

In this paper we introduce an algorithm for detection of straight edges with subpixel accuracy which has three steps: the sharpening of the image using a version of the Savitzky-Golay filter for smoothing and differentiation [7], the construction of a coarse edge image using Sobel filters [8], [9], and finally, the subpixel location determination fitting a Gaussian function to orthogonal sections of the coarse edge image. We will compare the proposed algorithm with two different versions of the detector, one that applies the Hough transform and another that applies second order polynomials to the Sobel coarse edge image instead of Gaussian fitting. The images under observation are photographs of a Nikon dark field autocollimator's reticle. Such reticle has exact interspacing between divisions, equal to 60 arcseconds, parameter that will be used to check the accuracy of the detectors.

(a) cross hair lines



(b) scale's reticle



(c) segmentation

Fig. 1: Different lines and edges: Panel (a), cross lines shown when measuring angles with a dark field autocollimator; Panel (b), measuring scale of a Nikon 6B dark field autocollimator; Panel (c) segmentation with Sobel edge detector.

This paper is organized as follows. Section II includes basic information about sub-pixel image processing and edge models. Section III outlines the successive steps of our proposed approach. Section IV shows the results of the edge detection on images taken with two different sensors, CMOS and CCD. We leave the conclusions to the last section.

II. Sub-pixel image processing

Most subpixel edge detectors that appear in the literature can be classified as part of one of the following groups: fitting, interpolation or momentum.

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Fitting methods: These methods define continuous functions for fitting the samples of the edge-generating curve by Ordinary Least Squares or Robust Regression [10]. Then, the position of the subpixel edge is found as the inflection points or center point of the continuous fitted function. Other fitting methods use local energy functions or wavelets to calculate the edge parameters, [2], [11], [12].

Interpolation methods: These methods achieve subpixel resolution interpolating the image to obtain a denser grid of pixels, [13]. Then the usual gradient detectors, such as Canny or Sobel, are applied to the enhanced image.

Momentum Methods: These consist in applying statistical momentums to determine the parameters of the proposed edge model. Usual methods are based on spatial momentums, such as Fourier-Mellin or Zernike, [8], [9], [14].

Interpolations and Momentum methods are appropriate for positioning edges in complex images, where edge curves have smooth but unpredictable behavior [8], [11], [12]. Examples of such problems are found when making maps, whether road maps or human blood vessel maps, extracted from remote sensed images or tomography images. In our case, the structure in our images is comprised of straight lines, i.e. curves with no curvature. Some of them, the ones from the autocollimator scale's reticle, are digital representations of lines precisely carved in glass. The ones that conform the cross are the results of digitalizing the reflection of collimated light. In both cases, cross sections of the lines show bell shaped curves, which correlate well with the nature of the lines.

Conventional edge detectors assume edges as boundary lines, thus, one dimensional cuts in the surface made orthogonal to the edge line show the shape of a step function, a ramp or a smooth curve, as the error function *erf*, [2], [6]. The images shown in Fig. 1 (a) and (b), are not boundaries of any object, so they have a different line model which could be assumed as a triangle, bell or parabola shape, as shown in Fig. 2. For these models, the location of each edge point at subpixel level is given by a parameter, or combination of parameters. For example, the Gaussian function has only one parameter governing the location of the edge while the parabolic function has two.

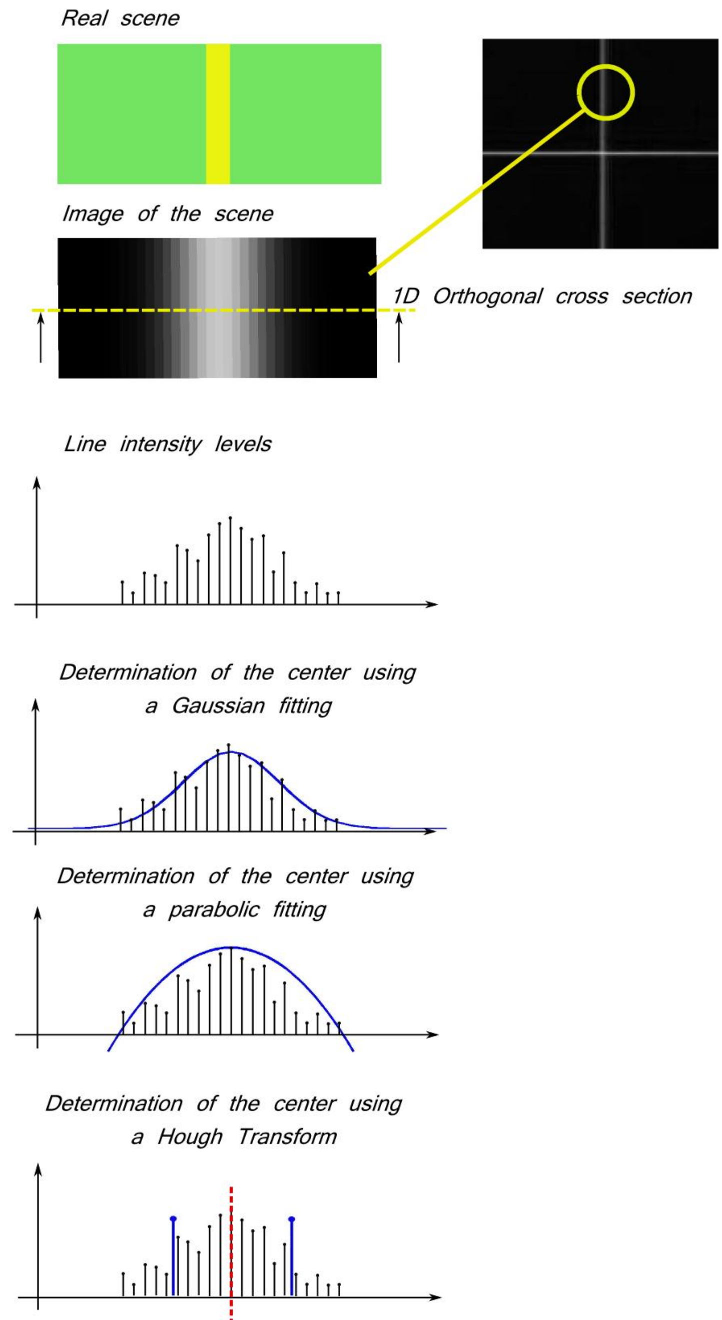

Fig. 2: General idea of proposed method using subpixel edge detection. Cross sections to the detected edge line are shown, with Gaussian fitting, parabolic fitting and Hough midpoint.

III. The Proposed Approach

A. Image denoising

The Savitzky-Golay filter is a digital filter designed for smoothing images [7], that is, increasing the signal-to-noise ratio without greatly distorting the signal. This is achieved in this paper by fitting successive sub-sets of adjacent data points with a second-degree polynomial by the method of linear least squares.

This step is of great importance, since barrel distortions and background noise can greatly reduce the accuracy of the subpixel location of the edges inside the detected pixel, when using fitting methods. Correlated residuals are the common consequence, and it may be avoided applying background substraction, lenses calibration or filtering.

B. Determination of the coarse edge image

Most sophisticated edge detection algorithms, like Canny edge detector, introduce edge linking steps to produce more connected edge lines. When dealing with subpixel applications, the coarse edge image must be as clean as possible, keeping strong edge points only. Thus, simple gradient base filters are most appealing choices. In this paper we work with Sobel filters S_x and S_y,

$$S_x = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix} \text{ and } S_y = \begin{bmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{bmatrix},$$

which are well known to preserve straight lines better, and given us better results than Prewitt and Roberts filters [8], [9]. These operators, when convolved with the image, produce gradient approximations in the horizontal and vertical directions respectively, which are are later searched for local maximum. Recoding the location of the local maxima, we produce a binary image of coarse edges in horizontal and vertical directions. These binary images are input data for refining edge location, using subpixel approximations, see Fig. 3. We only show Canny edge detection results for comparison purposes.

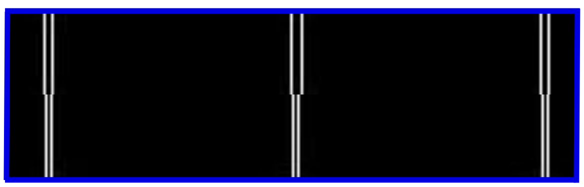

Fig. 3: Composite image with Canny edge detection (upper image) and Sobel edge detector (lower image), computed over the same set of lines of the reticle shown in Fig. 1

C. Refining edges to Sub-pixel Level

Sobel edge detection finds two sets of edge points for each line, see Fig. 2-last panel, located at pixel level on the inflexion points of the intensity surface. We use that information to infer the number of lines present in the image in each direction, vertical and horizontal, and their approximate position at pixel level. Such information is summarized in the coarse edge image that will be used differently when fitting template curves than when applying Hough transform.

1) Line profile fitting methods: In this step accurate location of the edge is approximated with continuous functions by robust regression [10]. Using the information of the coarse edge image at pixel level, we extract from the Savitzky-Golay filtered intensity image a linear neighborhood L (cross section) orthogonal to each pair of coarse edge boundaries; in particular, N pixels on each side of a coarse edge pixel pair are used, which isolate the line intensity profile. The location of the maximum of the fitted cross section function S_V determine edge location with sub-pixel accuracy, which in our case is a Gaussian function having three parameters: the centroid b, and the pair a and c which give the bell's height and breadth respectively,

$$S_V = a * \exp(-((x-b)/c)^2) \quad x \in L \tag{1}$$

In the literature, second order polynomials

$$S_V = A_1 x^2 + A_2 x + A_3 \quad x \in L \tag{2}$$

are also used for fitting when there is available only few samples in the neighborhood, caused by the coarse resolution of the camera, [12]. Blurred edges have also been sharpened by subpixel methods, fitting second order polynomials [6]. In these papers, it was pointed out that the size of the neighborhood can not be set arbitrary for all edges when fitting second order polynomials. In our own experiments, we observed that the number of samples must be in the order of 10, and the neighborhood must be symmetric with respect to the coarse edge position in order to estimate accurately the subpixel position. In Fig. 4 we show an edge curve, defined in a neighborhood of $N = 44$ pixels around a Sobel coarse edge pixel, Gaussian fitting, and quadratic fitting made with two different neighborhoods. We can see that the small centered neighborhood give a good estimate of the subpixel position of the edge point, but the biased neighborhood provides a biased estimate. Gaussian fitting was computed with all the data, proving to be insensitive to the size of the neighborhood.

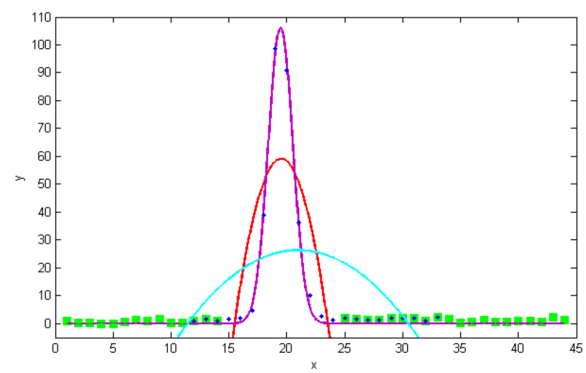

Fig. 4: Second order polynomial approximations to the cross section curve. In red, approximation made using a small symmetric L neighborhood (discarded values in green) centered on the coarse edge pixel. In cyan, approximation made using a biased neighborhood L (marked in blue). Gaussian fitting in purple was computed with all data.

2) Hough Transform: Applying the Hough transform to the coarse edge image is possible too, [1], [15]. The Hough line transform is widely used for detecting the locations and orientations of lines within an image. A set of collinear image points can be described by the equation

$$\rho = x\cos(\theta) + y\sin(\theta)$$

between the x-axis and this vector. For each image point (x, y) on a line, θ and ρ are constant. The transform is implemented by quantizing the Hough parameter space into accumulator cells. As the algorithm runs, each point (x, y) is transformed into a discretized curve and the accumulator cells which lie along this curve are incremented. Peak values in the accumulator array represent strong evidence that a corresponding straight line exists in the image. Unfortunately, the results of Hough Transform may not be sufficient for the edge location in practice. Even worse, the method gives many straight lines when detecting one edge.

Yimin et al.(2010) [15] proposed a hierarchical algorithm to detect corner points using Canny coarse image followed by Hough line segments detection, and refined the final binary edge image (composed only of straight segments) using least square fitting and the information about the global structure of the lines, since it conformed a mesh designed for camera calibration. This approach can be followed closely in the case of all measurement reticle related imagery, which have a known structure that can be used to refine the final edge image and locate line position at subpixel level.

In our case, we obtain profiles of each line segment detected by the Hough transform, and estimate the center line position as the midpoint between the two lines at subpixel level. We use then least square fitting to report a unique position. The result can be considered a weighting average of all found segments, since the transform selects the longest segments and provides one pixel wide edges located in the position of the inflexion points. If the appropriate line model is symmetric, the midpoint between both detected edges is a good estimation of the center of the line, see Fig. 2-last panel.

IV. Experimental data analysis

Results of edge detection with subpixel accuracy in images of the reticle of a dark field autocollimator Nikon 6D are presented in this section. We will use those values to compare the uncertainty in the measurement of Δ_X and Δ_Y, the distance between consecutive divisions of the scale of the Nikon 6D autocollimator, which represents 60 seconds of arc (1div=1min), in Horizontal (X) and vertical (Y) directions, see Fig. 6. These results are very important to calibrate machine learning measuring algorithms based on images taken from the reticle of the autocollimator. The method takes into account the structure of the lines to found, as we can see in Fig 5 as an illustration of our version of the Hough based method of [15].

The uncertainty in the estimation of Δ_X and Δ_Y in pixels/division is a good measure of the influence of the subpixels methods in measurement determination through machine vision. To found those estimates, we computed the mean center value of the subpixel position of each division of the center part of the scale shown in panel (c) of Fig. 1, in the vertical and horizontal position. We present the resulting estimated values in Table I.

TABLE I: Estimated values for parameters Δ_X and Δ_Y, with images taken with two different sensors, CMOS and CCD.

	Gaussian Fitting	Sobel-Hough	Canny-Hough
		CMOS sensor	
Δ_X	21.36 ± 0.06	21.37 ± 0.06	21.37 ± 0.08
Δ_Y	21.26 ± 0.06	21.25 ± 0.08	21.25 ± 0.1
		CCD sensor	
Δ_X	97.36 ± 0.04	97.28 ± 0.09	97.28 ± 0.1
Δ_Y	97.36 ± 0.039	97.28 ± 0.09	97.28 ± 0.1

We can transform the uncertainty values of this table to arcseconds with the equation

$$R_U = 60 \cdot \frac{U}{\Delta_{XY}} \tag{3}$$

Given that the autocollimator Nikon 6D has a maximum resolution of $R_A = 0.5$ arcseconds, the resolution ratio of our measurements is r_R:

$$r_R = \frac{R_A}{R_U} \tag{4}$$

In Table II and III we show this values, R_U and r_R for each sensor and method, giving more evidence that the Sobel-Gaussian method is the more appropriate subpixel method for estimating measurements through subpixel edge detection.

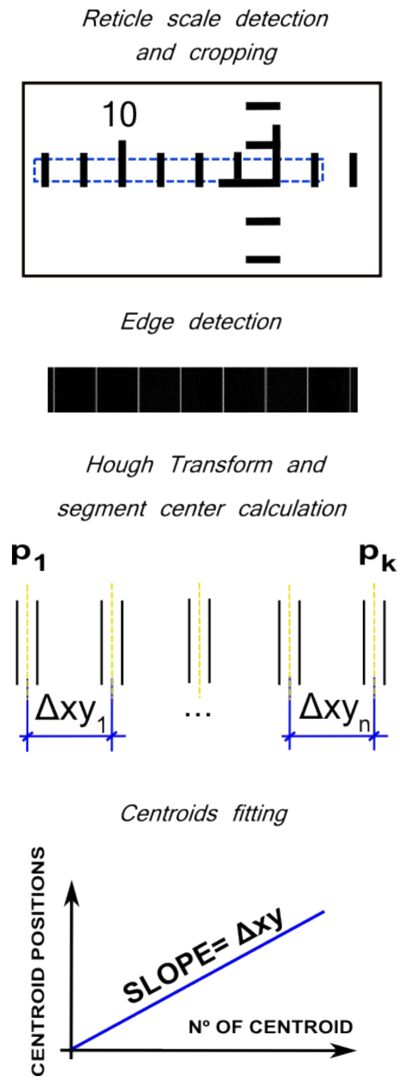

Fig. 5: Hierarchical Hough based method applied to calibration of machine learning measuring algorithm.

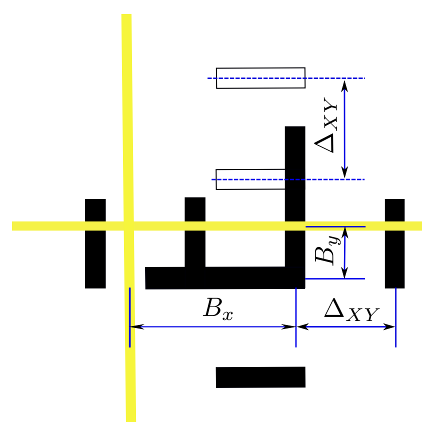

Fig. 6: Autocollimator's scale, Δ_X and Δ_Y are the distance between consecutive divisions in the horizontal and vertical scales.

TABLE II: Estimated values for the parameter R_U, with images taken with two different sensors, CMOS and CCD.

	Gaussian Fitting	Sobel-Hough	Canny-Hough
	CMOS sensor		
Δ_X	0.17	0.17	0.22
Δ_Y	0.17	0.22	0.28
	CCD sensor		
Δ_X	0.024	0.05	0.06
Δ_Y	0.024	0.05	0.06

TABLE III: Estimated values for the parameter r_R, with images taken with two different sensors, CMOS and CCD.

	Gaussian Fitting	Sobel-Hough	Canny-Hough
	CMOS sensor		
Δ_X	3	3	2.27
Δ_Y	3	2.27	1.78
	CCD sensor		
Δ_X	25	10	8,3
Δ_Y	20	10	8,3

V. Conclusion

In this paper, a method for determining the location of straight edges with sub-pixel accuracy was proposed. The method determines a coarse edge image using Sobel gradient masks and refines edge location to the sub-pixel level using robust statistical methods. Results of applying the proposed method to the location of the reticle lines from images of an autocollimator Nikon 6D prove that sub-pixel processing helps determining significant quantities related to automatic measurement. We compare these results with the outputs of a hierarchical Hough based algorithm that combines Hough line detection with least square fitting to detect the center point of a line. Even if these other methods tested here gave also accurate results when the camera resolution is low (the case of the CMOS sensor camera), they depend on more parameters that can not be always automatically set.

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