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ON THE REDUCTION OF SUB-PIXEL ERROR IN IMAGE BASED DISPLACEMENT MEASUREMENT

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Abstract – Image based measurement techniques allow for quick and contact-less measurement of single or multiple target displacement, shape, orientation and so on. The sub-pixel analysis increases the vision based displacement resolution. In the present paper resolution and uncertainty of 1D camera based displacement measurements is analysed, paying particular attention to the target geometry effect on the results. Comparison between camera based and laser interferometer displacement measurement is performed and some target modifications are tried, in order to reduce measurement uncertainty, due to sub-pixel systematic effect; the use of including the systematic effect into uncertainty, is wrong in theory but in practise often justified by the usual need of coarse and speed measurements.

The uncertainty in target displacement estimation given by three different image analysis algorithms is also tested in the case of rectangular, rhomboidal and circular targets.

Keywords: Sub-pixel, imaging, uncertainty

1. SYSTEMATIC EFFECT IN SUB-PIXEL ANALYSIS

Image processing is becoming one among the most common techniques in industrial process control and contactless measurement technique: this is mainly due to the increasing CPU capabilities, to the improvements in CCD sensors and the related electronics, and to the new post-processing image algorithms.

The main purpose of this paper is to look for a metrological qualification of a camera, as a displacement transducer. This is due to the fact that the above mentioned improvements have pulled image processing to performances comparable to those of some more traditional, well known and frequently used transducers.

In order to obtain accurate measurements both resolution and uncertainty must be considered because, as stated in Italian standard [1], high resolution is useless if uncertainty is larger than the resolution.

In order to improve the resolution capabilities of an image-based measurement system, two approaches are possible: increasing the CCD resolution (i.e. increasing the total number of pixels, but this usually contrasts with the dynamic properties) or applying a sub-pixel image processing. The number of pixels can be increased only up to a certain level, depending on the technical development of the CCD sensors, and imply an increase of the system cost. On the other hand, using a sub-pixel algorithm does not require a hardware improvement and it is usually cheaper. Of course both the pixel number increasing and the sub-pixel analysis can be applied together.

Even if applying sub-pixel analysis the available resolution of the vision-based measurement device can be very high (some software houses state that the maximum resolution obtainable using their routines is 1/50 of the pixel size, sometimes without explaining wich algorithm is applied), the uncertainty of the measured displacements is often worse ([2]), vanishing the resolution capabilities ([1]). It is in fact known in literature that, applying sub-pixel algorithms, a systematic effect is introduced in the measured data.

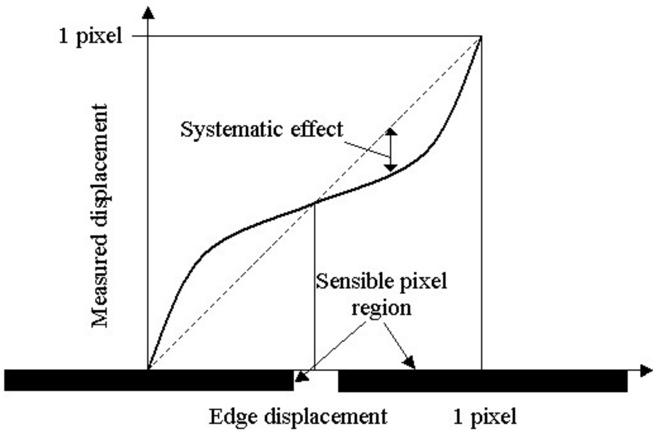

Fig. 1. Systematic sub-pixel effect

Some authors (see [2]) studied this phenomenon, trying to get the sources of the systematic effect. In 1994 Fryer ([3]) observed the phenomenon but no plausible explanation was clearly found. The only noticed correlation consisted in the fact that the effect is periodic, the period being coincident with the pixel side length (Figure 1). In 1998 Pedersini, Sarti & Tubaro [4] considered the effect due to the non photosensitive portion of the pixel area.

As a matter of fact, the measurement result is affected by a non-negligible systematic effect (see for example [2]). In literature a certain number of algorithms are described, able to compensate for this effect (see for example [4], [5], [6] and [7]). In order to apply this compensation, however, it is necessary to perform some tests on the optical part of the measurement chain (particularly lens and CCD sensor), and obtain the parameters of the compensating law.

Another possible approach, able to reduce the systematic effect, is intentional blurring: in this way the edge transition curve becomes smoother, and sub-pixel interpolation produces better results. This strategy, however, reduces the system capability of resolving details that are close each other, since blurring deteriorates the quality of the images ([4]).

The last approach, very commonly used by the software developers, is to comprise this effect in an uncertainty enlargement, a practice that, according to the ISO Guide to the expression of uncertainty in measurements ([8]) should be avoided whenever possible.

In this work the uncertainty of the camera-based acquisition device is analysed, in order to define the accuracy level and the effect of some important parameters on it, paying particular attention on target geometry. It is important to note that just the static properties will be considered, while the dynamic ones will be the object of a further paper.

Although with a camera it is possible to measure also 2D displacements of a number of objects (targets), in the present work only 1D displacement measurement is considered: the extension to 2D measurement is anyway possible, starting from 1D analysis.

2. EXPERIMENTAL SETUP

Tests on camera based displacement measurements were performed using a 1D-displacements motor-driven support for the target.

In order to evaluate the uncertainty properties of the vision device as a displacement sensor, measurements obtained with the camera are compared with those taken by a laser interferometer system (Fig. 2) used for linear displacement transducer calibration, with uncertainty of 0,3 μm. The laser interferometer is therefore a good reference for calibration of the camera with uncertainty up to a few μm that is an order of magnitude larger than the declared 0.3 μm for the interferometer.

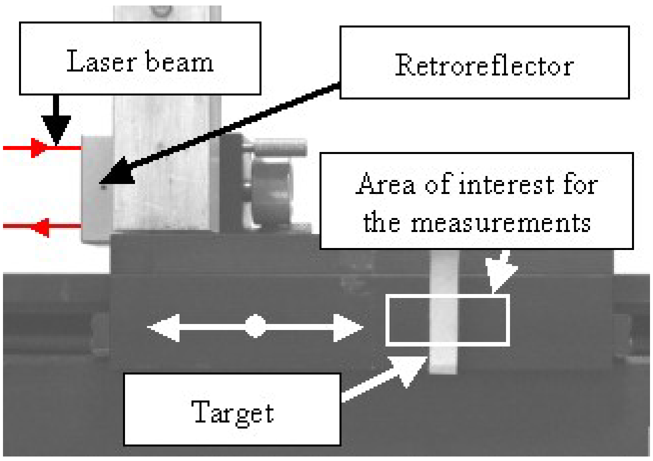

Fig. 2 Sliding support of the target and laser interferometer retro reflector (viewed from the camera under test)

The first part of the present paper shows an analysis of the common sub-pixel algorithms efficiency in giving displacement of a target, particularly considering the target geometry effect on the obtainable uncertainty.

In this research the attention is focused on very small displacements (i.e. few pixels); for that reason the eventual optical aberration is not considered and no distortion compensation algorithms are applied. If aberration compensation algorithms are applied the uncertainty linked to those algorithms must me accounted for too. Sometimes this uncertainty is larger than the one due to sub-pixel algorithms and can then become the main uncertainty source in the whole measurement chain.

3. SUB-PIXEL STRATEGIES

In order to measure the target position it is both possible to measure the position of an edge of the target or to measure the two edges and average the obtained values (see Fig. 3). This second option, applied to all the measurements shown in the present paper, produces measurements with lower uncertainty thanks to the average.

It is also possible to analyse just one pixel line or consider a number N of pixel lines in the performed measurement.

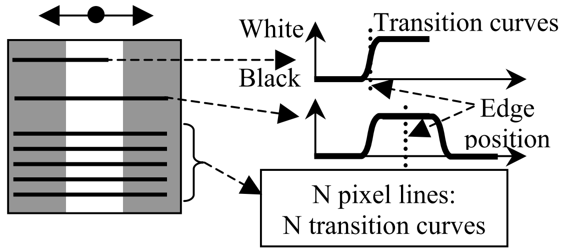

Fig. 3 One or two edge targets and single or multiple pixel line analysis

When N pixel lines are considered in the analysis, two possible approaches are available: the standard one (i.e. the one usually applied by the commercial image analysis libraries) is based on the average of the N transition curves to obtain an averaged transition curve to be used to estimate the edge position by applying the edge detection algorithm. In the following of the paper we will refer to this approach as the *"standard approach"*.

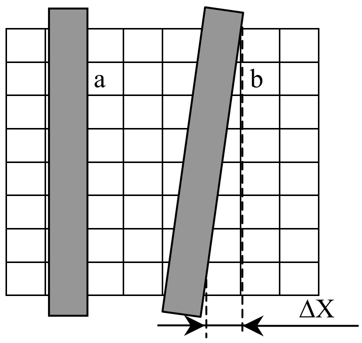

Fig. 4 Target edges parallel or angled with respect to the pixel grid

One different possible procedure is proposed in this paper in order to improve the measurement accuracy (as will be shown in the following paragraph); the idea is to estimate the edge position for each pixel line by applying the edge detection algorithm for each line and then to average the N obtained positions (this approach will be referred to as *"new proposed approach"*). It will be shown that, using this second approach in case of target edges non-parallel to the pixel lines (Fig. 4b), it is possible to reduce the systematic effect by averaging it out.

Since the systematic effect can produce an overestimation or an underestimation of the edge location, depending on the relative edge-pixel position (see Fig. 1), different pixel lines can produce opposite systematic effects. It is then possible to choose the number N of horizontal pixel lines so that, between the first and the last lines, the horizontal shift produced on the transition lines is 1 pixel (or an integer multiple of one pixel), as shown in Fig. 4b. Once averaged results from those N lines, the systematic effect can be compensated for. Some examples of the systematic effect compensation are shown in the following paragraph.

4. EXPERIMENTAL RESULTS WITH RECTANGULAR TARGETS AND EDGE DETECTION

In this paragraph some results are shown in the case of rectangular targets considering both the right and the left edges.

In Fig. 5 the systematic effect is clearly visible and no effect reduction can be obtained using the *new proposed approach* of extracting the edge position from each pixel line and averaging the results.

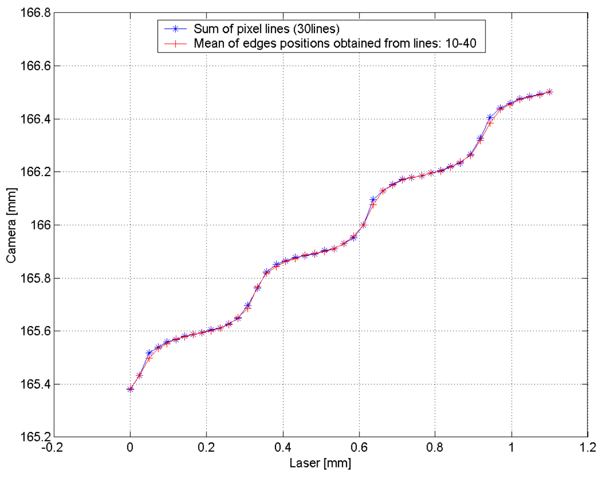

Fig. 5: Systematic effect with vertical-edge target

In order to underline and quantify the entity of the systematic effect the "deviation" is calculated as the difference between the "actual" displacement (measured with the laser interferometer) and the camera measured one. In Figure 6 the deviation is shown as a function of the reference displacement. Data shown in Figure 6 are those already shown in Figure 5, together with the data obtained considering just one pixel line.

In the case of vertical edge target measurements, no improving of the measurement accuracy with respect to the single line analysis can be obtained neither using the *standard approach* on 30 pixel lines nor applying the *new proposed approach*.

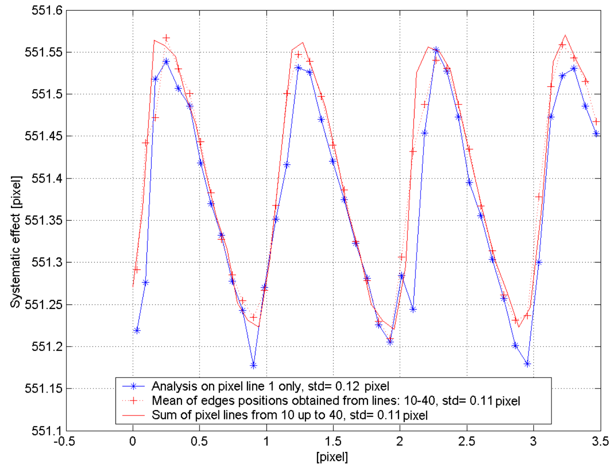

Fig. 6 Systematic effect considering one pixel line or 30 pixel lines with the standard and the new proposed approach

In order to investigate the edge rotation effect, the target was angled of 2.1 and 4.2 degrees. In this way the horizontal edge position is shifted of one and two pixels respectively (ΔX in Figure 4) between the first and the last considered horizontal line.

In case of 2.1° rotation, Fig. 7 shows the systematic effect when the standard algorithm (i.e. intensity pixel lines sum) is applied, together with the proposed approach results (edge detection on each single line and obtained position average).

The reduction of the systematic effect intensity is evident in the standard deviation values. Nevertheless the computation effort is higher in the latter approach, since the edge detection algorithm must be applied for each line.

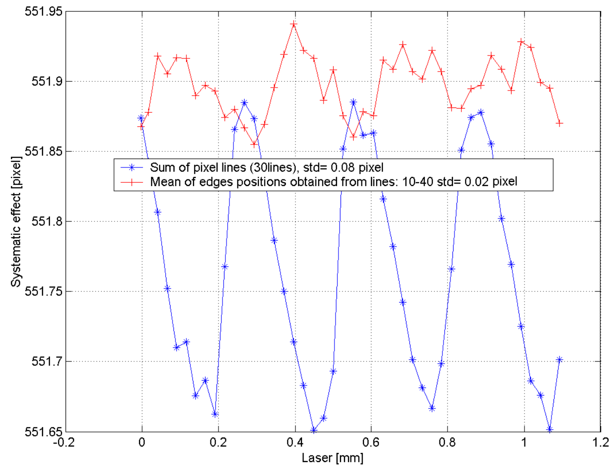

Fig. 7: Systematic effect in case of 2.1° rotated rectangular target

A further reduction of the systematic effect is obtained putting the target in an angle of 4.2°: in this case systematic effect is smaller than the random one (it is actually non visible), as shown in Figure 8.

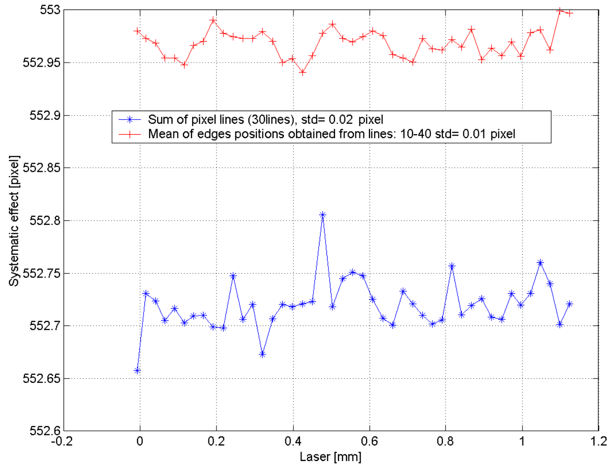

Fig. 8: Systematic effect in case of 4.2° rotated rectangular target

Tests on two edge targets show that the systematic effect due to sub-pixel error can be strongly reduced putting the target in an angle (i.e. not exactly parallel with the pixel grid).

5. SYSTEMATIC EFFECT MODIFICATION DUE TO TARGET SHAPE CHANGING AND DIFFERENT ALGORITHMS APPLICATION

In order to better understand the sub-pixel algorithm capabilities, tests using different target shapes have been performed and, for each target shape, three algoritms are applied: blob analysis, pattern matching and GMF (Matrox MIL library algorithm based on a Geometric Model Finder, [9]).

The considered target shapes are: square (this condition is actually the same to the one analysed in the previous paragraph), rhomboid and circular.

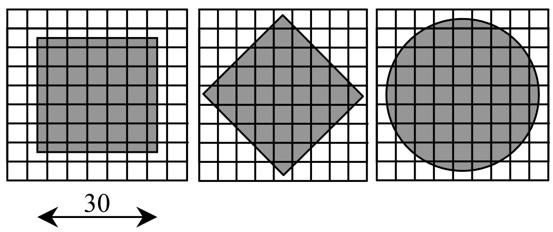

Fig. 9: Different tested target shapes

The detailed explanation of the adopted algorithms is not a goal of this paper but can be found in literature (see for example [10]).

In Figure 10 systematic effect is shown in the case of rectangular target, applying the blob analysis (BA), the pattern matching (PM) and the geometric model finder (GMF). In the legend the values of the estimated standard deviations "s" in pixel units are shown for each algorithm.

Analogously to Figure 10, in Figure 11 and 12 systematic effect is shown in the cases of rhomboid and circular target respectively.

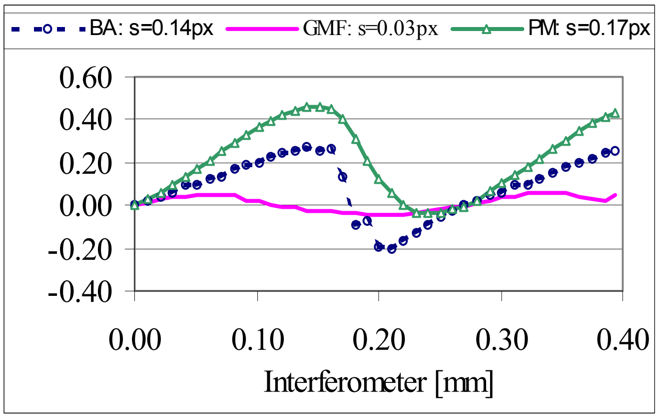

Fig. 10: Systematic effect with rectangular target with sides parallel to the pixel grid

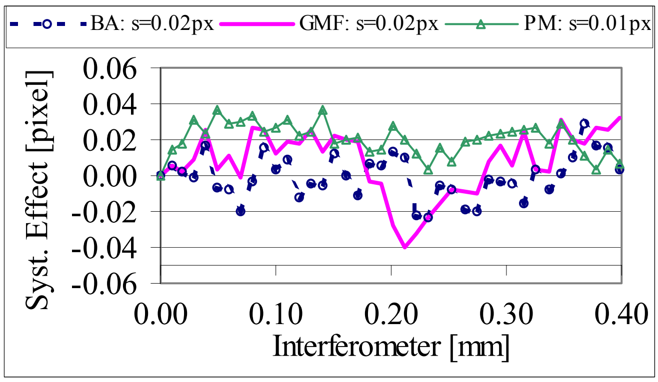

Fig. 11: Systematic effect with rhomboid target (square target 45° rotated)

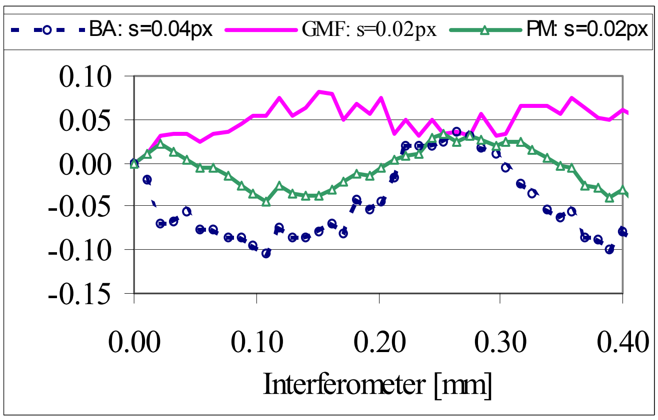

Fig. 12: Systematic effect with circular target

It can be seen that the systematic effect can be strongly reduced using a rhomboid target or a circular one, although the used algorithm is still very important.

The pattern matching algorithm ensures the best performances but request the maximum computation time.

Using the rhomboid target, however, the three algorithms show almost the same standard deviation, lower than the ones obtained with the other targets.

6. CONCLUSIONS

In this paper the systematic effect due to sub-pixel algorithm is analysed and an investigation on the best choices to improve results is proposed, in order to reduce the systematic effect intensity in 1D measurements. While in the case of rectangular target the proposed technique can be applied only when the marker orientation does not change during the target motion, when a circular target is adopted, the target angle is of course irrelevant. The uncertainty level associated with the standard and new measurement techniques was also measured, showing that a significant uncertainty reduction can be obtained, without the need of any error compensation algorithm, using angled or circular targets. The introduced approach allows to strongly reduce the start-up time of the vision-based measurement systems and permits the use of commercial sub-pixel routines

In the second part of the paper, different commercial algorithms were tested and uncertainty associated to displacement measurements were estimated, in case of rectangular, rhomboidal and circular targets.

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