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Calibration of a Microscopic Measurement System by Projection Technique of Coded Periodic Patterns

H. Bouali[1,2,*], Y. Belkacemi[1], M. Bouaziz[1], K. Mansouri[2]

[1] *Mechanical Engineering and Development Research Laboratory, National Polytechnic School, Algiers, Algeria*
[2] *Abbes Laghrour University, 40000 Khenchela, Algeria*

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The measurement based on the vision of periodic patterns by a remote camera is a more suitable solution for the control and characterization of micro robotic systems. In this way, we can take precise measurements without disturbing the measured objects and without the need for more devices and sensors that cause great confusion and clutter around the workspace. The technique of projection of the coded periodic patterns is perhaps effective and of good performance and especially in the case of a well calibrated system. Indeed, the question arises on the influence of the calibration on the results of measurement by this technique in terms of precision and uncertainty. Thus, the main purpose of this article is to study the influence of calibration on the measurement process, by deducing and calculating the committed error and the uncertainty rate. Based on an algorithm in MATLAB, we first create a coded periodic test pattern to which we apply a certain imposed displacement. Then, we project this pattern using a projection and reduction system on a digital camera which captures a photo and transmits it to a processing algorithm, which, in turn, calculates and deduces a value for the measured displacement. The repetition of this process occurs several times on the same imposed displacement (the same standard) to provide us with several measured values, this redundancy of the data allows us to draw a calibration curve and deduce several metrological parameters from our system of measure.

Keywords: Periodic pattern, Projection, LFSR code, Relative position, Absolute position, Calibration.

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1. INTRODUCTION

Measurement by contactless optical sensors is a new technique adapted in several technological fields, in particular, on a microscopic scale in order to avoid as much as possible the interaction between the sensor and the micro-object studied. Several actions are required at this scale, such as the positioning of micro-robots [1], measurement of micro-forces [2], assembly, positioning and manufacture of micro-opto-electro-mechanical systems (MOEMS) [3], measurement of nanoparticles [4], etc.

During the last ten years, scientists and researchers have tended to develop optical microscopic sensors intended for the characterization and manipulation of systems and robots at the microscopic scale. Among the fields that tend to develop these contactless sensors, we cite for example the field of micro-electro-mechanical systems (MEMS) [5], in which technicians have a greater need to carry out remote control operations and contactless measurements [6].

The periodic pattern measurement technique [7] is strongly recommended in these areas. Due to its dependence on the analysis of images taken from a distance without causing damage to the object, it is essentially based on the frequency analysis of two-dimensional sinusoidal signals in Fourier space, in order to detect the phase shift, the period and the angle of rotation [8]. The signal is presented in the form of an image of a pattern which consists of black or colored dots arranged on a white background. These dots are separated by a constant distance defined by the period of this signal in this direction. This method was subsequently developed and improved to widen its measurement range by adding special encryption to the signal, which made it possible to extend the capabilities of the method, in particular in terms of measurement range and in terms of resolution [9-11]. Other works have used the same principle of these sights to achieve nanometric precision at the level of continuous parallel robots [12].

We explain and develop in this paper a new complementary technique which is based on the assembly of the technique of periodic patterns and the technique of projection with reduction of these patterns on micro-objects in order to carry out measurements, positioning, assemblies or micromanipulations. One of the most important steps after joining these two techniques is the obtained system calibration. However, it is necessary to ask about the influence of this calibration on the measurement results. This is what we have tried to answer in the sections of this article.

In the first section, we briefly presented the design of periodic patterns and how to analyze them and deduce the position of the center of the image using the spectral analysis of Fourier, as well as the cryptanalysis, which offers the method a wide measuring range. Then, we presented the operating principle of the technique of micro-measurements by projection of periodic patterns and the different stages of generation, projection and acquisition of images of these patterns. The experimental device used for the validation of the technique and its calibration were also discussed in detail, with the different results obtained in the last sections.

*hichem.bouali@g.enp.edu.dz

2. MEASUREMENT PROSSES

The measurement process with periodic pattern projection is a precise and complex process and consists of several steps (Fig. 1) and each step depends on a certain technology, so we can distinguish four basic steps.

2.1 Generation of the Pattern

The generation of the pattern is carried out beforehand on the basis of a two-dimensional sinusoidal signal by the periods λ_x, λ_y and the initial phases ϕ_{x0}, ϕ_{y0}. This signal will be coded according to a specific coding (binary, LFSR, etc.) by removing the peaks corresponding to zeros and leaving the peaks corresponding to ones. In the end, the signal is converted into an image of dots ready for projection and analysis.

2.2 Projection of the Pattern

The pattern is projected using a projection system consisting of an image projector which projects the image onto a reducing lens, which, in turn, projects the reduced image onto a camera.

2.3 Image Acquisition

The image sensor is a CCD camera with a light sensor type CMOS placed at an appropriate focal distance to ensure the sharpness of the image. This distance is ensured by a linear positioner.

2.4 Image Processing

After image acquisition, it is transformed into a processing unit. The image processing algorithm performs two successive operations, a decoding operation and a comparison operation, with a reference image, to deduce and calculate a measured displacement. The displacement calculated in this phase will be compared with the displacement initially imposed in order to obtain a calibration curve.

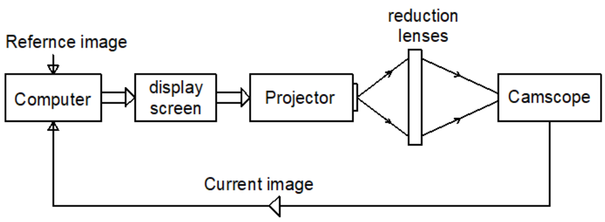

Fig. 1 – Principle of the technique of micromeasurements by projection of periodic patterns

Fig. 2 presents the motion simulation of an effector of a miniature micro-robot between two positions, the initial reference position (a) and the current final position (b). The goal of our work is the comparison between the two images in order to obtain the displacement performed by the effector.

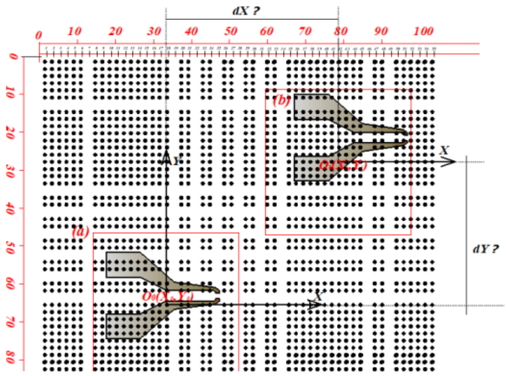

Fig. 2 – Movement detection of a micro-effector by projection of a periodic pattern: (a) reference initial image frame, (b) current image frame

3. CODED PERIODIC PATTERNS

The displacements d and y traveled by the effector are defined as the difference between the current position and the reference position, see Fig. 2:

$$\begin{cases} d_x = X_a - X_r, \\ d_y = Y_a - Y_r. \end{cases} \tag{3.1}$$

The couple (X_a, Y_a) is the center position of the current image, and the couple (X_r, Y_r) is the center position of the initial reference image.

On the other hand, the total displacement is the sum of the two absolute displacements d_{xa}, d_{ya} and the relative displacement δ_{xr}, δ_{yr}:

$$\begin{cases} d_x = d_{xa} + \delta_{xr}, \\ d_y = d_{ya} + \delta_{yr}, \end{cases} \tag{3.2}$$

such as

$$\begin{cases} d_{xa} = \lambda(K_x^a - K_x^r), \\ d_{ya} = \lambda(K_y^a - K_y^r), \end{cases} \tag{3.3}$$

where λ is the signal period length, K_x^a, K_y^a are the period numbers corresponding to the center positions of the current image along the x and y directions, respectively, K_x^r, K_y^r are the numbers of the periods corresponding to the center positions of the reference image along the x and y directions, respectively.

The relative displacements are written as follows:

$$\begin{cases} \delta_{xr} = (\delta_x^a - \delta_x^r), \\ \delta_{yr} = (\delta_y^a - \delta_y^r), \end{cases} \tag{3.4}$$

δ_x^a and δ_y^a present the relative displacement traversed by the center of the current image according to the x and y directions, respectively, δ_x^r and δ_y^r present the relative displacement traversed by the center of the reference image according to the x and y directions, respectively (Fig. 3).

So, we can finally write the expression of the total displacement in the form:

$$\begin{cases} d_x = \lambda(K_x^a - K_x^r) + (\delta_x^a - \delta_x^r), \\ d_y = \lambda(K_y^a - K_y^r) + (\delta_y^a - \delta_y^r). \end{cases} \tag{3.5}$$

3.1 Absolute Displacement

Table 1 presents the steps for decoding an image of a series of ordered points according to the LFSR code (linear feedback shift register) [8]. Noting that the reverse order of these steps is adapted to the first time for the generation and the creation, by a sinusoidal signal, of this coded test pattern (see subsection 2.1).

The example illustrated in Table 1 shows the steps followed to transform a code formed from dots to a sinusoidal signal and then to an LFSR code of zeros and ones. Then, compare the code obtained with another table that contains the decimal code of the corresponding periods. The difference between two values of a period gives us the number of periods moved by our image center.

We substitute this in Eq. (3.1) to find the absolute displacement traversed by the signal:

$$d_x = X_a - X_r = \lambda(24) + (\delta_x^a - \delta_x^r). \tag{3.6}$$

There remains in this equation only the determination of relative displacement $(\delta_x^a - \delta_x^r)$.

Table 1 – Example of decoding a periodic signal coded in the form of an image of points

	Reference image	Current image
Signal code		
Code by dots	•••••••• •• ••	••••••••••• ••
LFSR code	111111 110110 11	11111111111 0110
Corresponding period	$K = 18$	$K = 42$
Period deferenc	$K_x = 42 - 18 = 24$	

3.2 Relative Displacement

The relative displacement δ_x of a sinusoidal signal is shown in Fig. 3. It is the displacement less than an entire period which can be calculated from phase shift calculation with respect to a referential position and calculated by the following relationship:

$$\begin{cases} \delta_x = \dfrac{\lambda \phi_x}{2\pi}, \\ \delta_y = \dfrac{\lambda \phi_y}{2\pi}, \end{cases} \tag{3.7}$$

where ϕ_x and ϕ_y are the relative phases of the 2D signal.

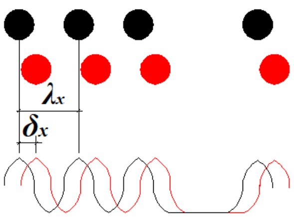

Fig. 3 – Relative displacement. Above, the reference points in the initial state (points in black) move to a final state (points in red). Below, this can be translated as a displacement of a coded periodic signal (example: 5-bit signal)

4. EXPERIMENTAL VALIDATION

To validate the method of projection of periodic patterns of displacements less than or equal to a period of time, an experiment is put into practice. This experiment aims to calibrate the technique in the range of a period, and therefore it is calibrated in the range of relative displacements.

The experiments are carried out in a metrology room (with temperature and hygrometry regulation). The practical device consists of a projector (CROSSTOUR P600 video projector, 2000 lm brightness, 60 Hz scan and 2000:1 contrast), a camera (SC 300, 3.1 MP 1/2" CMOS sensor, 3.2 µm square pixel), a macroscopic lens (TOKURA MC AUTO ZOOM 55 mm 1:3:9, f = 70-220 mm) and a target generated by a MATLAB algorithm is installed on a laptop (an 8th generation Intel® Core™ i5 processor). The algorithm thus makes it possible to acquire a series of images captured by the camera and then process them in order to obtain information on the movements of the target.

The results detailed in the following sections are obtained after a sufficient number of measurements (60 measurements for each imposed displacement), knowing that there are 15 imposed displacements to ensure the coverage of a period of 55 pixels.

5. RESULTS AND DISCUSION

5.1 Calibration of Measuring System

A calibration curve as defined in the international vocabulary of metrology VIM 2008: it is an expression of the relationship between an indication and the corresponding measured value. On the basis of this definition, the imposed displacements are taken as indications on the ordinate axis and the average of the values measured on the abscissa axis. According to 15 values ordered and regularly separated within a period λ = 55 pixels, we obtain the calibration curve shown in Fig. 4.

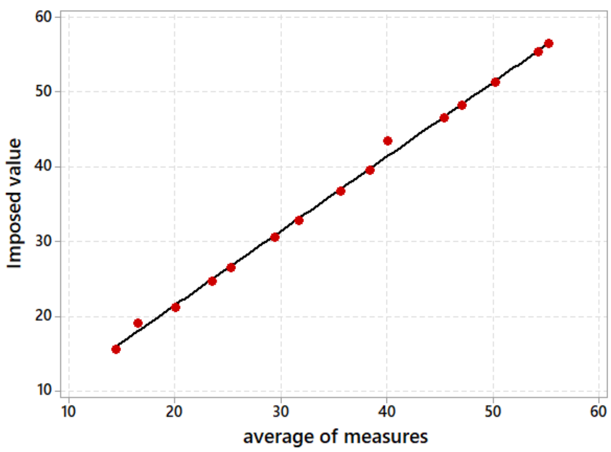

Fig. 4 – Calibration curve of the periodic pattern projection measurement procedure

The equation of this curve is determined by the least square method in the form:

$$\begin{cases} Y_i = (a_0 + a_1 \bar{X}_i) + R_i \\ i = 1{:}n \end{cases} \tag{5.1}$$

Here i is the measurement number, n is the number of measurements carried out, $(\bar{X}_i, Y_i)$ is the couple of the average of the measured values and the imposed displacement, R_i are the residuals of the model or the random part of the model.

The application of the least squares criterion aims to determine a_0 and a_i in such a way as to minimize the square sum of deviations:

$$SSD = \sum_{i=1:n}^{n} R_i^2 = \sum_{i=1:n}^{n}(Y_i - (a_0 + a_1\bar{X}_i))^2. \quad (5.2)$$

After replacing $(\bar{X}_i, Y_i)$ values, a polynomial is obtained as a function of a_0 and a_i as follows:

$$SSD = \mathrm{f}(a_0, a_1). \quad (5.3)$$

Finally, we have the following calibration function:

$$Y = 1.551 + 0.994\,X. \quad (5.4)$$

This function is used to predict and approximate the measured values Y according to the imposed values X without making measurements.

5.2 Distribution Law

In order to prove the law of normal distribution of the measured values with respect to the imposed values, we examine the probability diagram and look at whether the distribution closely follows a straight line or not.

And this is clearly seen from Fig. 5, which shows the property of normality over a confidence interval encompassing 60 % of the measurements.

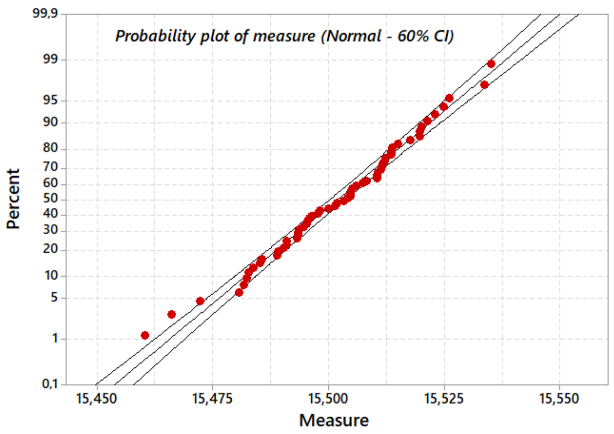

Fig. 5 – Probability diagram

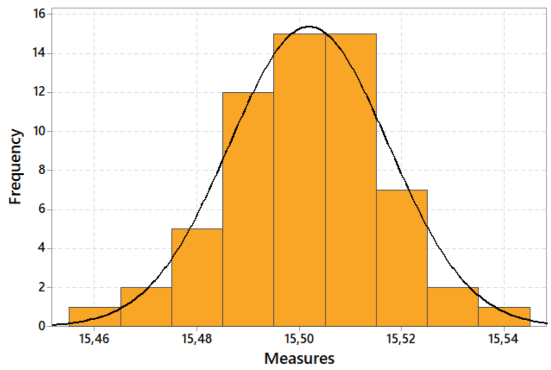

Fig. 6 – Normal distribution of measured values

Alternatively, the normal distribution of the measured values around the mean value is shown in Fig. 6. Taking as an example the measurement of the imposed value $X_{imposé} = 15$ pixels, this measurement is carried out 60 times, therefore with an image rate every 20 s.

The average value of these measurements $\bar{X} = 15.5$ pixels with a standard deviation $\sigma = 0.0156$ pixels or approximately 0.05 μm.

5.3 The Standard Deviation

Note in Fig. 7 that the measured values are varied around the average value of 15.50 pixels, therefore by a constant error of about 0.50 pixels. This error is called systematic error and is the result of several factors affecting the performance of the measurement process.

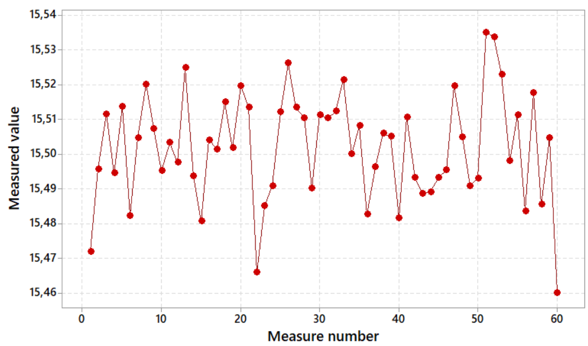

Fig. 7 – Variation of the measured displacement value according to the measurements (example: 60 measurements for the imposed displacement $d_x = 15$ pixels)

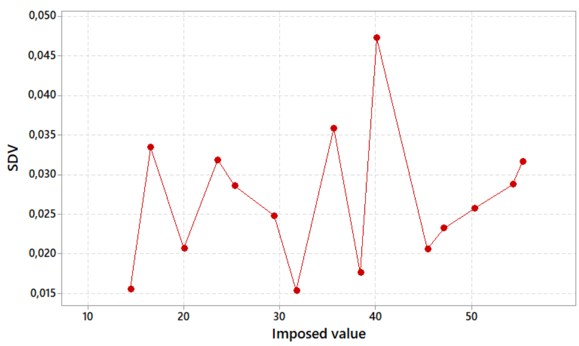

Fig. 8 – Variation of the standard deviation for each imposed value

6. CONCLUSIONS

This article presents a new in-plane micromeasurement technique using a vision-pattern system with nanometric resolution and a wide range. It offers us unlimited possibilities in the use of different types of charts in terms of size, shape and color. Unlike traditional manufactured targets, which are characterized by their limited use and the impossibility of modifying their properties according to the appropriate conditions of use.

Calibration of this measurement system is one of the necessary conditions to improve the quality of measurement and increase the precision from microns to a few nanometers. We have also defined the calibration equation by the least squares regression method. This equation allows us to predict the value of the measure before its implementation and in this way, we can predict the position of the mobile robot and thus control it more precisely and in real time.

In this work, we have fully calibrated the measurement system without addressing calibration of each part of the system separately, and this is what can be studied in the future, since the camera, projection system and reduction system will be calibrated separately to identify the main source of errors.

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Калібрування мікроскопічної вимірювальної системи методом проекцій закодованих періодичних шаблонів

H. Bouali[1,2], Y. Belkacemi[1], M. Bouaziz[1], K. Mansouri[2]

[1] *Mechanical Engineering and Development Research Laboratory, National Polytechnic School, Algiers, Algeria*
[2] *Abbes Laghrour University, Khenchela, 40000, Algeria*

Вимірювання, засноване на баченні періодичних шаблонів дистанційною камерою, є більш придатним рішенням для контролю та визначення характеристик мікророботизованих систем. Таким чином ми можемо проводити точні вимірювання, не порушуючи вимірювані об'єкти та не потребуючи додаткових пристроїв і датчиків, які створюють велику плутанину та безлад у робочому просторі. Метод проекцій закодованих періодичних шаблонів є ефективним та має хорошу продуктивність, особливо у випадку добре відкаліброваної системи. Дійсно, виникає питання про вплив калібрування на результати вимірювання цим методом з точки зору точності та невизначеності. Таким чином, основною метою статті є дослідження впливу калібрування на процес вимірювання шляхом виведення та розрахунку допущеної похибки та рівня невизначеності. На основі алгоритму в MATLAB ми спочатку створюємо закодований періодичний тестовий шаблон, до якого застосовуємо певне накладене зміщення. Потім ми проектуємо цей шаблон за допомогою системи проекцій та зменшення на цифрову камеру, яка фіксує фотографію та передає її алгоритму обробки, який, у свою чергу, обчислює та виводить значення для виміряного зміщення. Повторення цього процесу відбувається кілька разів для того ж самого накладеного зміщення (того ж самого стандарту). Така надлишковість даних дозволяє нам намалювати криву калібрування та вивести декілька метрологічних параметрів із нашої системи вимірювань.

Ключові слова: Періодичний шаблон, Проекція, Код LFSR, Відносне положення, Абсолютне положення, Калібрування.