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On-Line Diagnostic Tools for CMM Performance

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The on-line evaluation of the degradation of a coordinate measuring machine (CMM) performance, either due to variations of environmental factors, or to the deterioration of one of the CMM subsystems, is particularly important for the machine user. A sign of this interest is the large number of international standards that have been issued. The paper presents an approach for the on-line diagnostic of the metrological capabilities of a CMM. The method, which does not make use of additional internal or external instrumentation, is performed on-line during a normal measurement cycle. The graphical approach of the method, based on the use of control charts, permits a simple and immediate monitoring of the machine performance. Preliminary experimental results are presented and discussed.

Keywords: CMM performances; Control charts; On-line diagnostics; Quality

1. Introduction

Coordinate measuring machines (CMMs) are instruments which are able to carry out dimensional measurements, and to verify the deviation from geometric specifications of objects that can have very complex shapes.

CMMs are able to operate completely automatically. Their main characteristics are programmability and flexibility. These properties make them useful in today's manufacturing cells with no human operator. In these situations, the preservation of metrological characteristics over time is fundamental [1–3].

The on-line evaluation of the deterioration of these characteristics, owing to variations of environmental factors, or to the deterioration of one of the CMM subsystems, is particularly important for the machine user. A sign of this interest is the large number of international standards that have been issued [2,4–7].

In this paper, we present an innovative approach for on-line diagnosis of CMM performance, which is able to identify potential deterioration of performances [8–10].

The method makes no use of additional internal or external instrumentation. The only information used is that produced during the normal measurement cycles. It is different from the normal periodic off-line tests performed using external equipment [11,12]. The method can be automated without difficulty and performed on-line during a normal measurement cycle [13,14].

Some preliminary experimental results are reported and analysed in the final section of the paper.

2. CMM Performances Verification

The most important criteria when evaluating a method for the verification of CMM performances are:

- the time required.
- the cost and the complexity of the equipment.
- the training level and qualification of the operators.

The quality of information produced by a specific verification method increases with the duration of the test and the complexity of the equipment used. This extends from very rapid tests to the complete calibration of a CMM, which can require some days. The diagnosis of CMM performances therefore implies the search for a trade-off between the increasing duration of the test (prevention of anomaly situations) or a decrease (test costs) of the verification frequency.

The on-line detection of a CMM deterioration has two advantages. First of all, it may indicate the need for a more accurate test only when really necessary. Secondly, it can verify the "guarantee" that the dimensions of the measured part are really those indicated by the CMM. On the other hand, the periodic verification does not detect the instant at which a damage-state occurs, nor the cause of the damage [15].

According to ISO 10360 [7], a CMM can typically be subjected to three types of test:

1. The initial verification or acceptance test.
2. Periodic verifications.
3. Irregular/occasional checks.

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Common elements of these verifications are the use of complex and costly test equipment, and the need to operate off-line when the machine is not working. These considerations result in the desire for an on-line method that, with the above verification strategies, is able to display to the operator automatically the occurrance of deterioration in the machine performance.

3. The Method

The main goal of the on-line diagnosis of CMM performances is the detection of the deterioration caused by changes of environmental conditions, degradation of some machine subsystem or variation in the measurement cycle (including the positioning of the workpiece in the measuring volume). The effect of the degradation of the performance of the machine is the production of non-reliable measurements.

The purpose of the method is to develop a test which is able to use the machine measurements as a "diagnostic tool" to detect the specific condition of a CMM. The idea is to observe how a parameter connected to the performances of the machine varies over time [16–18]. In particular, we propose to use as an indicator the characteristic of reproducibility of the coordinates of a point with a changed path of the touch-probe subsystem [19].

Factors which can influence CMM reproducibility are the geometry of a part, the operating conditions of the machine subsystems, the aligning method used for the reference system, the environmental conditions and the physical position of the measurement points in the operating volume of the machine.

A drift of the reproducibility indicator from the "normal" operating condition signals the occurrence of a variation of one of the above listed factors (assignable causes).

Let us define $\mathbf{P}^k(x,y,z)$ as the kth reproduction of the coordinates of a certain nominal point $\mathbf{P}^1(x,y,z)$, measured for a changed path of the touch-probe subsystem. The reproducibility of a CMM is a random variables (r.v.):

$$R^{(k)} = d(\mathbf{P}^1,\mathbf{P}^k) \quad (\forall k = 1,\ldots,t) \tag{1}$$

where $d(\mathbf{P}^1,\mathbf{P}^k)$ is the Euclidean distance operator between the reference point and its kth reproduction in the working volume, and t is the number of reproductions.

Taking into account a single contribution to the reproducibility, we can write:

$$R^{(k)} = G^{(k)} + M^{(k)} + A^{(k)} + C^{(k)} + P^{(k)} \tag{2}$$

where $G^{(k)}$ represents the contribution to the variability by the part geometry, and $M^{(k)}$ is the contribution by the CMM subsystem, $A^{(k)}$ is the contribution by the alignment of the reference system on the part, $C^{(k)}$ the contribution by the environmental conditions affecting the measured object, $P^{(k)}$ the contribution by the measurement point position in the working volume of the machine.

Using the hypothesis of the independence of all variable sources, if $\sigma^2_{R^{(k)}}$ is the variance of $R^{(k)}$, the following equation holds:

$$\sigma^2_{R^{(k)}} = \sigma^2_{G^{(k)}} + \sigma^2_{M^{(k)}} + \sigma^2_{A^{(k)}} + \sigma^2_{C^{(k)}} + \sigma^2_{P^{(k)}} \tag{3}$$

similarly, for the expected value of $\mu_{R^{(k)}}$ of $R^{(k)}$

$$\mu_{R^{(k)}} = \mu_{G^{(k)}} + \mu_{M^{(k)}} + \mu_{A^{(k)}} + \mu_{C^{(k)}} + \mu_{P^{(k)}} \tag{4}$$

In the absence of sources of variability, for an ideal CMM and an ideal part, we should have: $\sigma^2_{R^{(k)}} = 0$ and $\mu_{R^{(k)}} = 0$.

In practical applications, $R^{(k)}$ is distributed with an expected value $\mu_{R^{(k)}} > 0$ and has a variance $\sigma^2_{R^{(k)}} > 0$. These values depend on the structural configuration of the machine, the part geometry, and the environmental operating conditions.

The distribution of $R^{(k)}$ is not normal, and it cannot be negative. However, as a first approximation, the normality assumption produces results not far from the exact distribution of $R^{(k)}$.

If during CMM operation, one or more factors make relevant changes to their contribution to the reproducibility characteristic, then the measurement process cannot yield "credible" information [16]. A sufficient, but not necessary, condition that a CMM yields unreliable measurements is that its reproducibility undergoes a variation from its own natural tolerance.

The continuous observation of $R^{(k)}$ permits the monitoring of the performance of the whole CMM/environment/part subsystems with respect to some reference conditions. Useful tools able to monitor together the central tendency and the dispersion of the random variables $R^{(k)}$ are process $\overline{X} - R$ control charts [20].

From an operating point of view, we can proceed as follows. Let us define s as the total number of measurement points collected on the surface of a workpiece, and n as a random subset of s over which to carry out the reproducibility tests. These latter form the sample from which to build the $\overline{X} - R$ control charts. The frequency of verification is established on the basis of the part complexity and the measurement costs. A simplified model for the computation of the test frequency can be found in [10].

The method is subdivided into two phases: control chart setting up, and process reproducibility monitoring. Reproducibility tests are spaced out during the normal measurement cycle of a workpiece, according to the following steps:

- part positioning.
- reference system alignment.
- measurement cycle and reproducibility tests execution.
- part removal.

Points out-of-control or anomalous behaviour of reproducibility parameters are pointed out at the time to the operator.

With the aim of discriminating each single variability contribution, a series of reproducibility tests on an external witness-part are also executed during the measurement cycle. As a result we can obtain an estimation of the two main contributions to the random variable $R^{(k)}$:

1. The component due to the machine reproducibility, represented by the terms $M^{(k)}$ and $P^{(k)}$.
2. The remaining component due to the measuring cycle, represented by the terms $G^{(k)}$, $A^{(k)}$ and $C^{(k)}$.

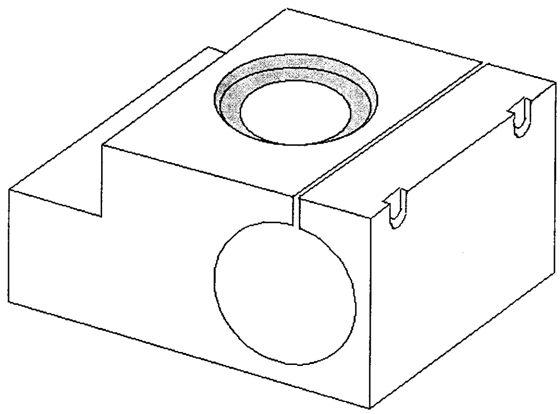

Fig. 1. Scheme of the workpiece used for the experiments.

The main characteristics of the proposed method can be summarised as follows:

- continuous estimation of a CMM metrological performances, without waiting for periodical verifications.
- on-line identification of assignable causes of variability.
- graphical approach by means of control charts.
- economic and reliable technical solution.

4. Preliminary Results

The experimental work was aimed at verifying the capability of the control charts to recognise anomalous operating conditions, by means of the reproducibility tests.

Tests have been performed using a CMM – DEA model IOTA 0101 Standard motorised version – available in the laboratory of the Department of Manufacturing Systems and Economics at the Polytechnic University of Turin. The machine has a moving bridge structure, with a measuring volume up to 555 mm in the *X*-axis, 610 mm in the *Y*-axis, and 410 mm in the *Z*-axis.

Figure 1 shows the workpiece used to investigate the method. It is stainless steel, with its main side 150 mm long and with two holes of 80 mm diameter through the block. A 15 mm diameter sphere has been used as an external witness-part. The two objects have been positioned in the same measurement volume.

A measurement cycle of $s = 45$ points has been programmed. The sample sizes considered for the reproducibility tests are $n = 5$ for the workpiece and $m = 5$ for the witness-part. The selected test-points are a random subset of the measurement points. The reproducibility test has been repeated every 15 measurement points.

After a preliminary investigation, we observed that the choice of the sample points selected for the reproducibility test is not crucial for the method. The use of a random subset of the measurement points allows the application of the method to a sequence of mixed parts.

In order to facilitate the experimental tests, a software program has been developed. It allows the automatic alignment of the reference system and the storage of the point coordinates of the measurement cycle.

To simulate the "normal" operating conditions of a production line in a job-shop, the tests have been carried out without the use of an air-conditioning system (temperature and humidity controls). For each measurement cycle, 3 reproducibility tests have been carried out. The measurement cycle has been repeated 20 times, for a total of 60 tests both for the workpiece and the witness-part.

Figures 2 and 3 show the $\bar{X} - R$ control charts for the reproducibility tests, respectively, for the witness-part and the workpiece, in the absence of external disturbances. They show the natural process variability. In these conditions, the charts indicate a very small central value.

Figures 4 and 5 show the $\bar{X} - R$ charts for an out-of-control situation due to a progressive increase of the room temperature. The charts manifest a high sensitivity. Their control limits are restrictive enough to detect any minimal variation due to mechanical factors or environmental changes.

Figures 6 and 7 show the $\bar{X} - R$ charts for the external witness-part and a simulation of an inspection of 20 workpieces. In particular, Figure 7 illustrates the effects of the

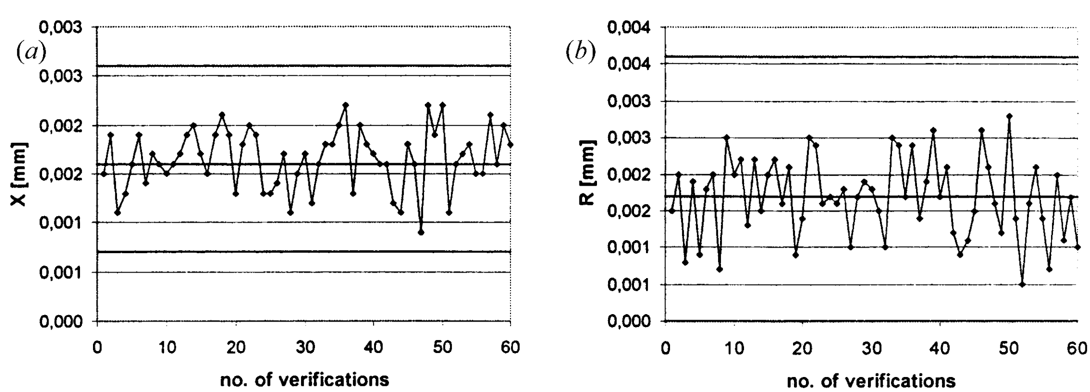

Fig. 2. (*a*) $\bar{X}$ and (*b*) *R* charts of the reproducibility tests for the external witness-part. The figure shows the natural variability of the process without assignable disturbance causes. The process is in control. Control chart limits are determined on the basis of the first 20 samples. Three tests have been carried out for each measurement cycle.

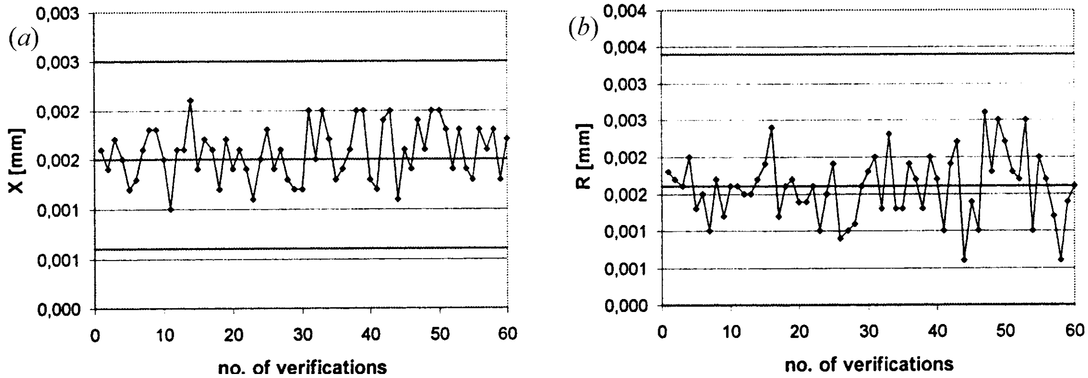

Fig. 3. (*a*) $\overline{X}$ and (*b*) R charts of the reproducibility tests for the workpiece after the alignment of the reference system to the measured part (see Fig. 1). The figure shows the natural variability of the process without assignable disturbance causes. The process is in control. Control charts limits are determined on the basis of the first 20 samples. Three tests have been carried out for each measurement cycle.

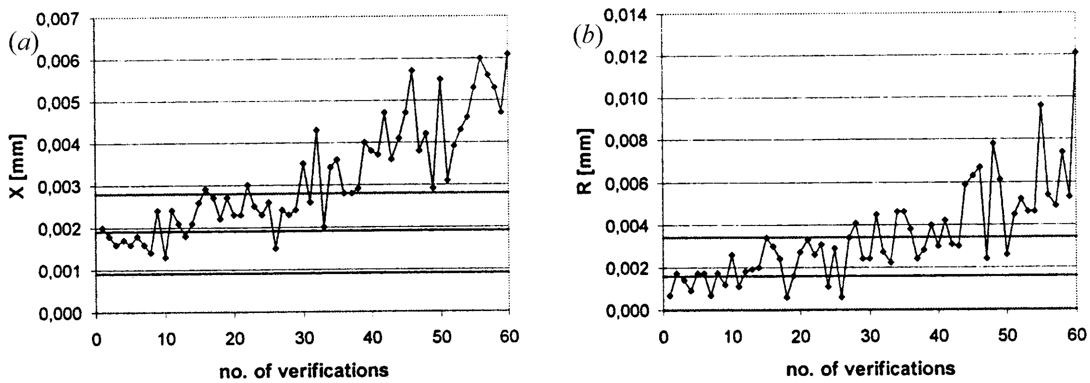

Fig. 4. (*a*) $\overline{X}$ and (*b*) R charts of the reproducibility tests for the witness-part subject to a progressive increase in room temperature. The process is out of control. Control chart limits are determined on the basis of the first 20 samples. Three tests have been carried out for each measurement cycle.

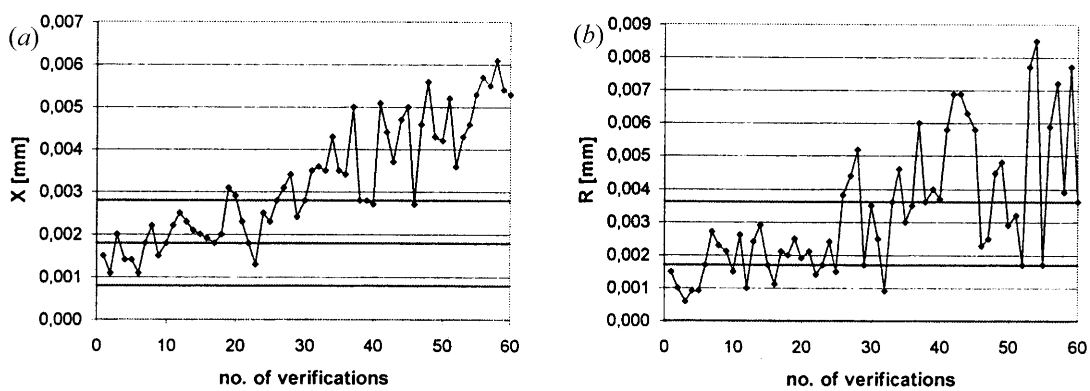

Fig. 5. (*a*) $\overline{X}$ and (*b*) R charts of the reproducibility tests for the workpiece subject to a progressive increase in room temperature, after the alignment of the reference system to the measured part (see Fig. 1). The process is out of control. Control charts are determined on the basis of the first 20 samples. Three tests have been carried out for each measurement.

activities carried out during the measurement process of a part on a production line which are:

- place the workpiece within the measuring volume (part positioning).
- set up the coordinate system for the workpiece (reference system alignment).
- measure each feature of the workpiece (measurement cycle execution).
- remove the workpiece from the CMM (part removal).
- introduction of a new part in the measuring volume, and so on.

The results obtained show the variability contribution due

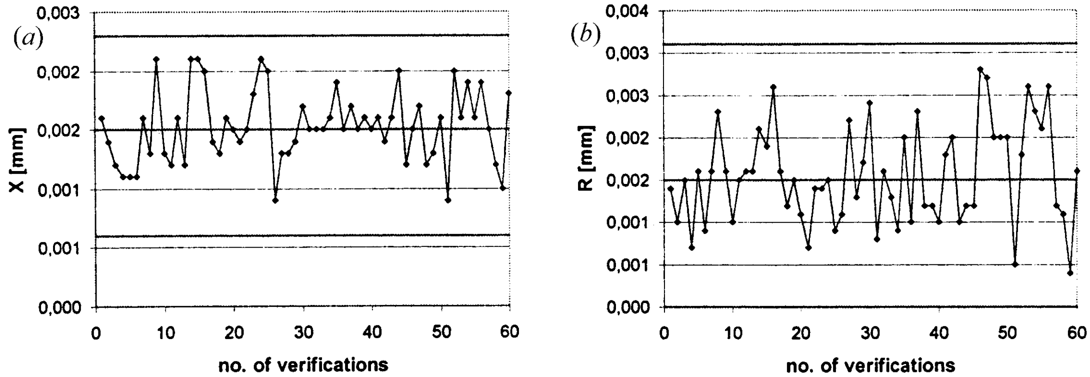

Fig. 6. (*a*) $\overline{X}$ and (*b*) *R* charts of the reproducibility tests for the external witness-part during a measurement process of several successive parts on a production line. The process is in control. Control chart limits are determined on the basis of the first 20 samples. Three tests have been carried out for each measurement cycle.

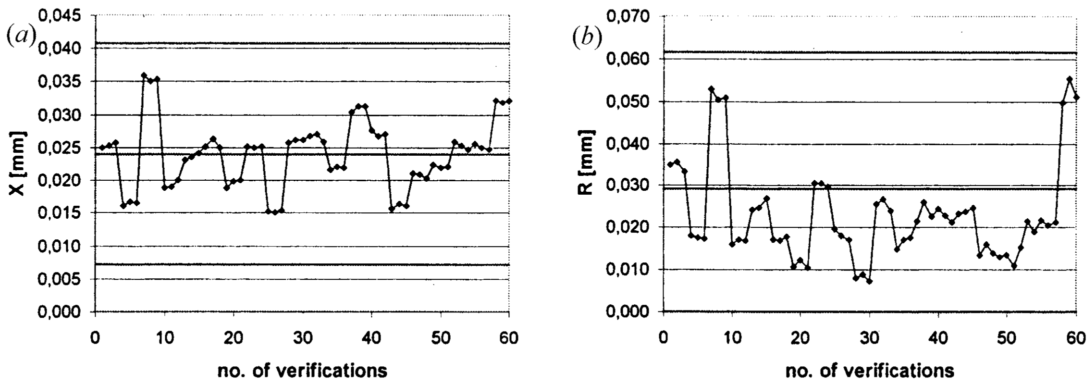

Fig. 7. (*a*) $\overline{X}$ and (*b*) *R* charts of the reproducibility tests for the workpiece during a measurement process of several successive parts on a production line. The observed discontinuities reveal the effects of the positioning of a new part. The process is in control. Control chart limits are determined on the basis of the first 20 samples. Three tests have been carried out for each measurement cycle.

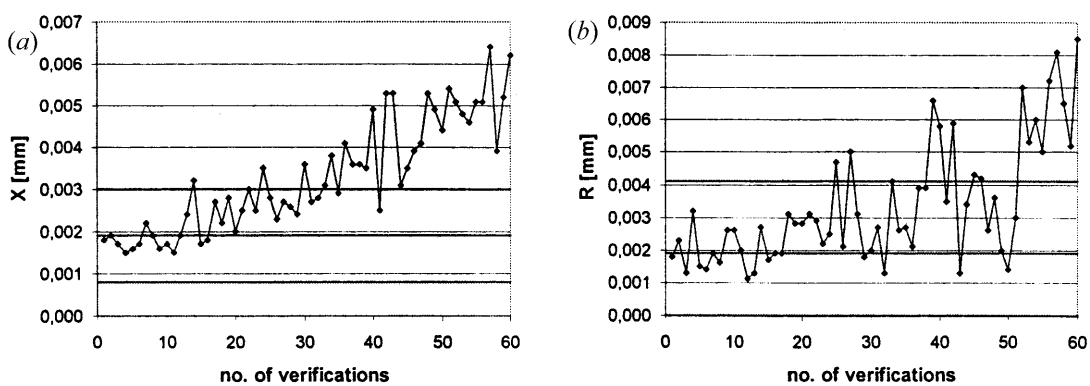

Fig. 8. (*a*) $\overline{X}$ and (*b*) *R* charts of the reproducibility tests for the witness-part during a measurement process of several successive parts on a production line, subject to a progressive increase in room temperature. The process is out of control. Control chart limits are determined on the basis of the first 20 sample. Three tests have been carried out for each measurement cycle.

to the positioning of new workpieces on the production line. The sets of triple points shown are relevant to the three reproducibility tests associated with each measurement cycle. Both the tests on the workpieces and on the external witness-part reveal that the process is in control. Furthermore, from the analysis of the two charts we can determine the variability contributions due to the different sources. For the external witness-part, the only source of variability is the natural CMM reproducibility; on the other hand, for the workpiece, variability shown by the charts contains all contributions coming from the measurement process.

Figures 8 and 9 show the reproducibility tests for the witness-part and the workpiece during the measurement process of a set of successive parts from a production line, subject to

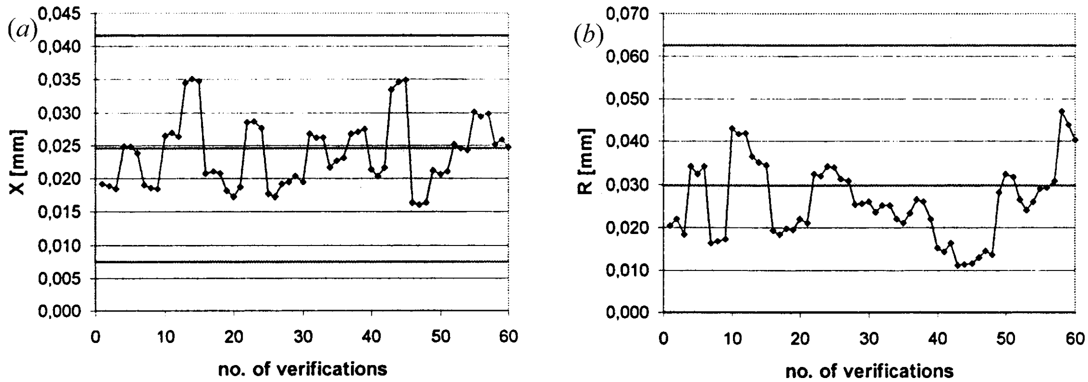

Fig. 9. (*a*) $\tilde{X}$ and (*b*) R charts of the reproducibility tests for the workpiece during a measurement process of several successive parts in a production line, subject to a progressive increase in room temperature. The observed discontinuities reveal the combined effects of the positioning of a new part and the increase of the temperature. The process appears in control. Control chart limits are determined on the basis of the first 20 samples. Three tests have been carried out for each measurement cycle.

a progressive increase of room temperature. The discontinuities observed reveal the combined effects of the positioning of a new part and the increase of temperature. The witness-part process is out-of-control, whereas the workpiece process appears in control. The variability due to the increase of temperature is so small that it is not "visible" in the workpiece charts.

In conclusion, the use of a witness-part relies on a specialisation of diagnostics. It allows the allocation of the total variability to each single source factor.

5. Conclusion and Future Developments

The possibility of an on-line deterioration evaluation of the metrological characteristics of a CMM, owing, for example, to variations of the environmental factors or to damage of some components, is a very important requirement for a machine user.

The paper presents a method which is able to diagnose anomalous working conditions of the machine/environment/part subsystems. The use of an external witness-part allows the discriminating of the source of anomalies affecting the results of a measurement cycle.

The graphical approach, using control charts, permits a simple and concurrent monitoring of the machine performance.

However, the methodical application of the reproducibility test increases measurement cycle-time of a part. So, in order not to increase the cycle-time too much, it is possible to have a discretionary limit on the frequency of the test.

Further developments of the method are aimed at complete automation of the proposed diagnostic procedure.

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