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An investigation of the repeatability of nonrigid parts measurements: A case Study of an aluminum panel

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Abstract

Nonrigid parts are traditionally mounted on over-constrained holding fixtures during inspection in order to support the part and maintain an acceptable level of measurements repeatability and reproducibility. The fixture's over-constrained configuration and restraining sequence are critical characteristics of the fixture and can become active components of the measurement system. Therefore, this paper investigates the profile measurements repeatability of an aluminum flat panel with respect to these aforementioned characteristics. To this end, this paper studies the measurements variability of the panel mounted on four over-constrained fixture configuration, each with two different restraining sequences.

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1. Introduction

Measuring nonrigid parts is a difficult task if insufficient fixing constraints are applied to maintain the part during the measurement process. Inspection fixtures for such parts often use a N-2-1 locating scheme (i) to position the part (ii) to ensure the part is stable, and (iii) to maintain an acceptable level of repeatability of the measurements results. By using more contact reference points (N>3) than mathematically necessary to position the part, these fixtures violate the isostatic positioning principal and are therefore commonly referred to as over-constrained fixtures. As an example, Fig 4-42 of the American Society of Mechanical Engineers (ASME) Y14.5 standard [1] illustrates a part that must be restrain on such over-constrained fixture.

The amount and position of these additional references (i.e. datum), as well as the fixture's restraining sequence, are critical design variables of the fixture. Finding the optimal fixture configuration design is a major aspect of the Computer Aided Fixture Design (CAFD) research field. Substantial literature exists in the field, as review by Boyle *et al.* [2] and Wang *et al.* [3]. For example, Raghu and Melkote [4] study the effect of the fixture clamping sequence; Chen *et al.* [5] optimise the fixture layout design and clamping force; Cai *et al.* [6] investigate the challenges introduced by the lack of rigidity of nonrigid parts during the design of their over-constrained fixture.

Although these studies take into account the fixture configuration, they focus on manufacturing holding fixtures and the error these fixtures introduce into the manufacturing process. As such, they do not investigate the effect the configuration of inspection fixture has on the measurement system error.

In order to quantify the measurement system error, measurements repeatability and reproducibility studies are commonly performed. Measurements repeatability refers to variability of the measurements obtained by one person while measuring the same item repeatedly. It is common to distinguish the repeatability error into the error due to the equipment – the static repeatability, and

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the error due to the measurement procedure and loading/unloading of the part − the dynamic repeatability [7]. Measurements reproducibility represents the variability of the measurement system caused by differences in operator behavior.

To the authors' knowledge, only the Auto/Steel Partnership (A/SP) Body Systems Analysis Project Team [7] published a paper analysing the influence of the inspection fixture design on the measurements error of nonrigid parts. In their study of an automotive body side outer panel, it was found that 85-90% of the observed gage errors can be attributed to the measurements dynamic repeatability (i.e. loading/unloading of the part).

Given the frame-like shape of the part used in the Auto/Steel Partnership team study, a question arises as to whether the study conclusion can be extended to parts with a continuous shape used typically in the aerospace industry, such as a fuselage panel. To this end, this paper investigates the measurements repeatability of an aluminum panel with respect to the amount of fixture's contact references points, and the fixture's restraining sequence. Accordingly, four over-constrained fixture configurations are studied, each with two different restraining sequences. From these experimental studies, this paper examines (i) whether the over-constrained configuration significantly influences the measurements repeatability, (ii) whether the restraining sequence significantly impacts the measurements repeatability within an over-constrained configuration, and (iii) whether the measurements repeatability varies in space within a part and an over-constrained configuration. Finally, the study findings are compared to Auto/Steel Partnership Body Systems Analysis Project Team study [7].

Before any substantive discussions can transpire from this paper, it is necessary to take a moment to explain the way in which it will unfold. Section 1 has introduced the challenges involved in inspecting the geometric and dimensional requirements of nonrigid parts with acceptable measurements repeatability. Having established these challenges, Sec. 2 details the case studies by defining the case study part and describing the methodology used. Section 3 analyses the results to show the effects the fixture's over-constrained configuration has on the measurements repeatability. Finally, Sec. 4 expands on the outcome of this research.

2. Case study

This section describes the experiment that has been conducted in order to investigate the measurements repeatability of an aluminum panel. The test panel and its inspection fixture were designed and manufactured by the École de Technologie Supérieure in Montreal, Canada. A detailed description of the test panel, inspection fixture and experiment methodology follows.

2.1. Definitions

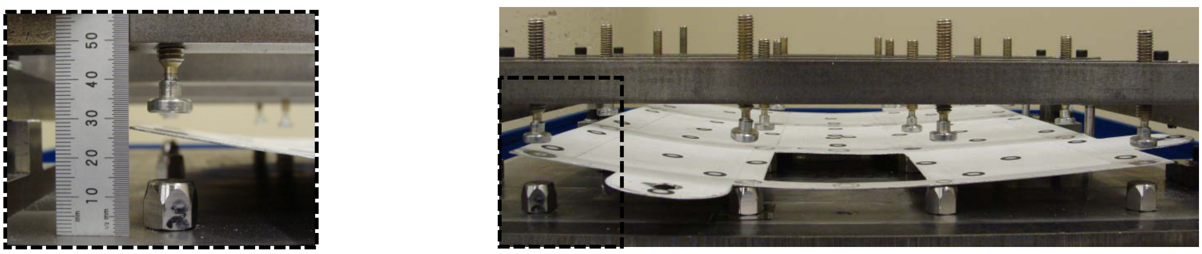
2.1.1. Part

The considered case study is a 7075 aluminum flat panel of 304.8 mm [12 inch] width by 406.4 mm [16 inch] of length as shown in Fig. 2a. The panel has a thickness of 0.762 mm [0.03 inch] and has eight main 0.254 mm [0.01 inch] deep pockets. The part reference frame is constituted by the primary datum plan A, the secondary datum B and the tertiary datum C.

In a free state, the part shape varies significantly from its nominal flat shape, see Fig. 1. An over-constrained fixture is therefore necessary to adequately evaluate the surface profile of the part.

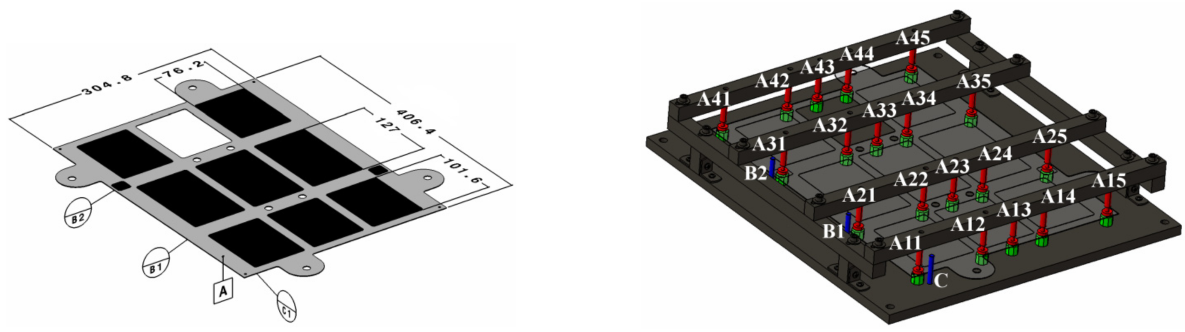
2.1.2. Fixture

The fixture used to maintain the test panel during inspection has been designed to enable the representation of the part primary datum A to be modified according to over-constrained configuration envisioned. Accordingly, the fixture can simulate the part primary datum A using between three to twenty fours datum targets represented by ∅ ¼ inch rest pads. The secondary and tertiary are simulated by the fixture using respectively two and one ∅ ¼ inch dowel pins.



(a) (b)

Fig. 1. Test panel in a free state on the fixture (configuration IV)



(a) (b)

Fig. 2. (a) Test panel description; dimensions are in mm, light regions are 0.762 mm thick; dark region are 0.508 mm thick
(b) Detail of the experimental inspection fixture

The contact between the part and the reference frame is maintained using swivel-foot spindles. Fig. 2b illustrates the experimental inspection fixture.

2.2. Methodology

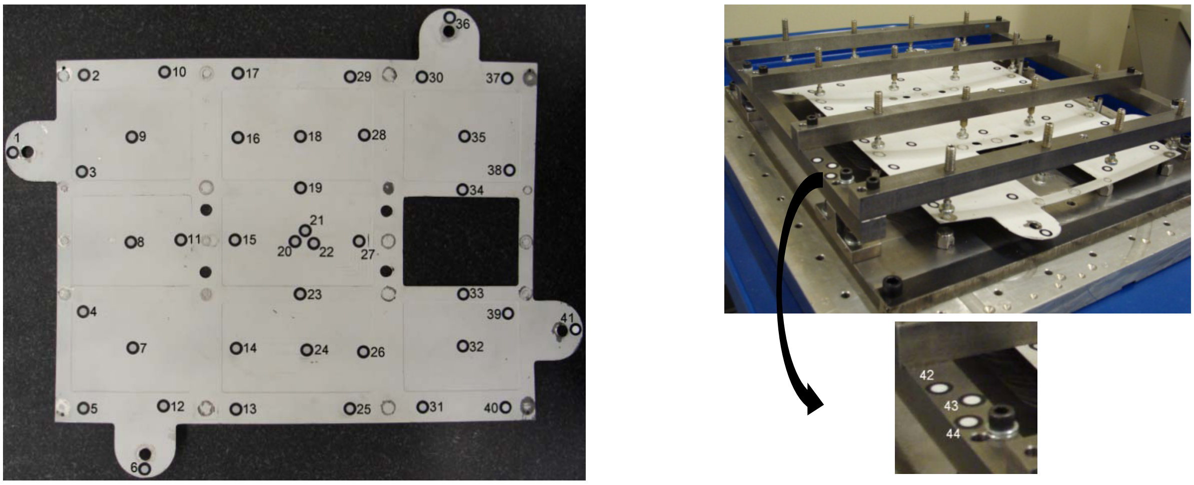
The objective of this research is to investigate the measurements repeatability of the surface profile of a nonrigid aluminum panel with respect to the fixture's over-constrained configuration and restraining sequence used during the part measurement. To perform this investigation, the test panel is measured on the fixture using four over-constrained configurations with two different restraining sequences for each configuration. The over-constrained configuration respectively call for the use of four, eight, twelve and sixteen datum targets to represent the part primary datum **A**. Using the nomenclature in Fig. 2**b**, Table 1 details the fixture's configurations and restraining sequences. These restraining sequences have been randomly generated.

Before measuring, the part is restrained on the fixture using a three-pass procedure. First, after loading and positioning the part on the fixture, the part is restrained within approximately a quarter of inch of the fixture datum targets **A**. Next, the part is repositioned to ensure the contact with the fixture datum **B** as well as **C**, and then constrained on the fixture datum targets **A**. Finally, the restraining sequence is repeated to ensure that the part is properly fixed. Once the part is fixed, measurements are performed with a Metris LC50 laser probe mounted on a CMM.

For each fixture configuration, measurements are randomly repeated thirty times (30): fifteen times (15) for each fixture restraining sequence. The panel is therefore loaded/unloaded on the fixture and measured one hundred and twenty times (i.e. $4_{config.}$ x $2_{seq.}$ x $15_{scan/seq.}$ = 120). Forty five (45) positioning targets where placed: 41 are on the part and 3 are on the fixture. These targets ensure a correspondence between the setup and minimize the uncertainty in selecting the same point a cross each setup. The position and nomenclature of these positioning targets are shown in Fig. 3. The center points of these targets are used in this investigation; however, points 1·6·36·41 proved to be unreliable and are therefore excluded from the measurements repeatability analysis.

Table 1. Description of the fixture's configurations and restraining sequences

Fixture configuration	Datum targets **A**	Restraining Sequence 1	Restraining Sequence 2
I	A11 A15 A41 A45	A15 A41 A45 A11	A11 A15 A45 A41
II	A11 A15 A41 A45 A22 A24 A32 A34	A11 A34 A24 A41 A45 A32 A15 A22	A32 A22 A11 A34 A24 A15 A45 A41
III	A11 A13 A15 A21 A23 A25 A31 A33 A35 A41 A43 A45	A13 A23 A45 A21 A33 A35 A41 A11 A31 A25 A15 A43	A35 A31 A21 A45 A11 A33 A25 A23 A41 A15 A43 A13
IV	A11 A12 A14 A15 A21 A22 A24 A25 A31 A32 A34 A35 A41 A42 A44 A45	A45 A41 A31 A35 A42 A12 A11 A32 A14 A34 A15 A21 A24 A22 A25 A44	A32 A15 A31 A41 A25 A12 A44 A35 A14 A45 A11 A42 A22 A21 A34 A24



(a) (b)

Fig. 3. Position of the forty five (45) positioning targets: (a) 41 on the part (b) 3 on the fixture

Furthermore, positioning targets 42·43·44 have been measured between each loading/unloading of the part on the fixture. Accordingly, these targets have been measured two hundred and forty times (i.e. $4_{\text{config.}}$ x $2_{\text{seq.}}$ x $15_{\text{scan/seq.}}$ x 2 = 240). In doing so, the measurement system static repeatability is more accurately assessed.

3. Results and Discussion

From the experimental studies, this section analyzes (i) whether the over-constrained configuration effects the measurements repeatability (ii) whether the restraining sequence influences the measurements repeatability within an over-constrained configuration (iii) whether measurements repeatability of the targets is influenced by their distance from the fixture restraints, and (iv) whether the study findings agree with the Auto/Steel Partnership study conclusions [7].

3.1. Over-constrained configuration vs. Measurements repeatability

To assess the influence of the fixture over-constrained configuration, the measurement system's dynamic repeatability standard deviation under each fixture configuration must be compared. The dynamic repeatability is a function of the static repeatability and the observed repeatability (i.e. total), as expressed by Eq. 1. Accordingly, the static repeatability ($\sigma_{\text{static-repeatability}}$) and the total repeatability ($\sigma_{\text{Repeatability}}$) standard deviations are first computed using Eq. 2.

$$\sigma_{\text{Dynamic-reapeatability}} = \sqrt{\sigma^2_{\text{Reapeatability}} - \sigma^2_{\text{Static-reapeatability}}} \qquad (1)$$

$$\hat{\sigma}_{\text{Reapeatability}} = \frac{\overline{Range}}{d_2^*} \qquad (2)$$

where $\overline{Range}$ is the average range et d_2^* is a constant based on the number of trials and the number of parts, see ref. [8].

The static repeatability standard deviation is assessed using the positioning targets 42·43·44 measurements. The average measurements variation range for these three targets is 0.0739 mm. Using Eq.2 with the value of d_2^* equal to 3.80537 [8], the measurement system static repeatability standard deviation is estimated at 0.0194 mm. The estimated value is consistent with the specification of the measurement instrument provided by the manufacturer.

The total repeatability is estimated for each fixture configuration and restraining sequence using the average of the measurements range value of all the targets on the panel and a value of d_2^* equal to 3.553 [8]. Estimated total repeatability values are given in Table 2. Total repeatability values for measurements with the fixture configuration ***I*** are not estimated as they are found to be too unstable to allow a proper evaluation. Also excluded from the estimated total repeatability values computation of Table 2 are measurements of the targets 10·17·29·30 when the part is fixed according to configuration ***II***. The reason is that measurements from these four (4) targets display a particularly high and unstable variability compared to the rest of the targets for this particular fixture configuration. The position of these 4 targets suggests that the high variability observed is caused by the presence of the two dowel pins representing datum **B** on the fixture.

Table 2. Estimated value of $\sigma_{\text{Repeatability and}}$ $\sigma_{\text{Dynamic-repeatability}}$ for each fixture configuration and restraining sequence*

Fixture configuration	1st Sequence		2nd Sequence	
	$\sigma_{\text{Repeatability}}$	$\sigma_{\text{Dynamic-repeatability}}$	$\sigma_{\text{Repeatability}}$	$\sigma_{\text{Dynamic-repeatability}}$
I	n/a	n/a	n/a	n/a
II**	0.0381	0.0327	0.0366	0.0310
III	0.0154	Insignificant	0.0172	Insignificant
IV	0.0121	Insignificant	0.0121	Insignificant

* Values are in mm
** Measurements results of points 10-17-29-30 are excluded.

At last, the dynamic repeatability standard deviation for each fixture configuration and restraining sequence are estimated using Eq. 1 with the estimated static repeatability and total repeatability values. Table 2 summarizes the total repeatability and dynamic repeatability standard deviation estimated values.

Finally, it can be inferred from the estimated dynamic repeatability standard deviation values in Table 2 that the over-constrained configuration has an effect on the measurements repeatability and more specifically, that the variability of the measurements are reduced when using a more constrained fixture configuration. Furthermore, Table 2 suggests that for a sufficiently constrained fixture configuration (i.e. configuration ***III*** and ***IV***), the measurements repeatability is not influenced by the loading/unloading of the part on the fixture. These conclusions are supported by examining the measurements variability of each positioning targets for each fixture configuration and restraining sequence shown in Fig. 5.

3.2. Restraining sequence vs. Measurements repeatability

The fixture restraining sequence insignificant effect on the measurements repeatability can be inferred by analyzing Fig. 5 and Table 2. Fig. 5 shows there is no significant difference between the measurements range value at each target when the part is mounted on the fixture using the restraining sequence **1** (in blue) and **2** (in red). Note that the fixture configuration ***I*** necessitates more repeated measurements (i.e. >15) to assert the influence of the restraining sequence. Table 2 also shows no significant difference in the values of the total repeatability and dynamic repeatability standard deviation between the restraining sequences. Furthermore, since the fixture with the configuration ***III*** and ***IV*** revealed to have no effect on the measurements repeatability (i.e. insignificant $\sigma_{\text{Dynamic-repeatability}}$), it is coherent that in those cases the fixture restraining sequence has no influence on the measurements repeatability.

3.3. Measurements repeatability vs. Position

To investigate whether the targets measurements repeatability are influenced by their distance from the fixture restraints, Fig. 4 shows the measurements variability range for the fixture configuration ***II***. The fixture configuration is chosen here as the part is not too constrained on the fixture. Fig. 4 suggests that the variability of the measurements increases in regions further away from the fixture constraints.

3.4. Findings vs. A/S Partnership study

Finally, it can be seen that the paper's overall findings agree with those of the Auto/Steel Partnership study, more specifically, (i) that the use of additional restraints to fix the part reduces the measurement variability and (ii) that regions next to a fixture's constraints exhibits less measurements variability. However, this study revealed that the restraining sequence has no significant influence on the measurements repeatability; this finding does not agree with the A/S Partnership study's conclusion. The A/S Partnership study on a quarter inner panel showed that when the restraining sequence of three clamps where changed, the measurements variability of regions next to these three clamps changed while the measurements variability of regions further away remained unchanged.

One possible explanation for these conflicting conclusions is that they are due to the different types of shapes and overall sizes of the parts used in both studies. Compared to continuous surface part, frame-type shapes rigidify more locally when constrained. Moreover, the part in the A/S Partnership study is much larger, complex and nonrigid than the test panel in this study and tends naturally to have more measurements variability.

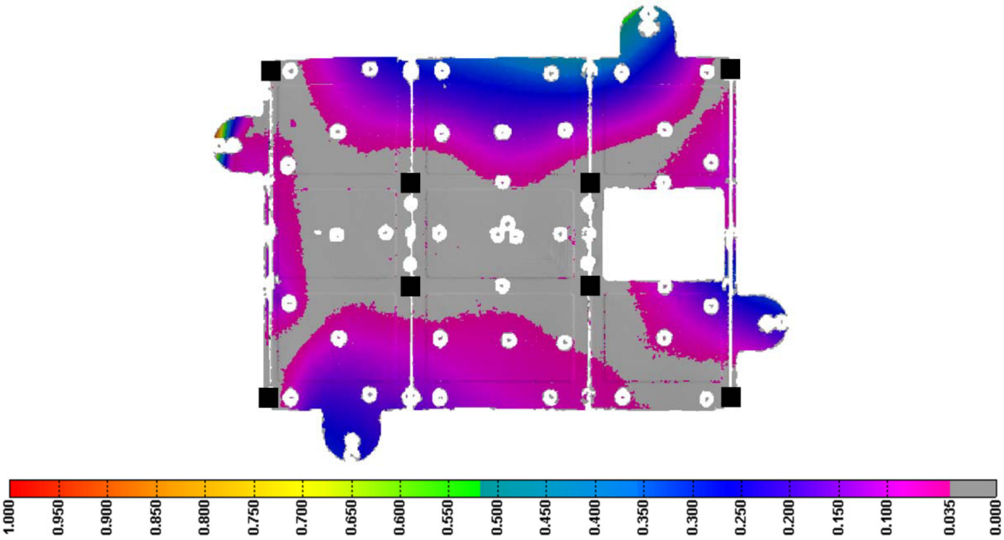


Fig. 4 Measurements variability range for the fixture's configuration ***II*** using both restraining sequences (in mm); Restraints are marked by black squares

4. Conclusion

By varying the over-constrained configuration and restraining sequence of an aluminum panel inspection fixture, this study has shown that inspection fixture design can be an important contributor to the measurement system error. For example, if the case study panel has had a profile tolerance of 0.762 mm [0.03 inch], the gage repeatability with configuration ***II*—1st** restraining sequence, would account for 25.75% of the tolerance with a confidence interval of 99% (i.e. 5.15·0.0381/0.762=25.75%). On the other hand, the gage repeatability of the fixture for which the loading/unloading of the part has no influence (e.g. configuration ***IV*—1st** restraining sequence), would account for only 13.11% of the tolerance with a confidence interval of 99% (i.e. 5.15·0.0194/0.762=13.11%).

Moreover, this investigation found that the measurements variability is reduced when additional restrains are used to fix the part and those regions further away from the fixture's constraints exhibit higher measurements variability.

Furthermore, this study concluded that the restraining sequence had no significant impact on the measurements repeatability for the test panel. Although this conclusion seems to support the practice of not imposing a retraining sequence during the mounting of a panel on its inspection fixture, it should not be generalized given the effects that the shape and nonrigid behavior of the parts can have on the measurements repeatability. This comment is reinforced by the Auto/Steel Partnership study.

In conclusion, depending on the nonrigid part geometry and its inspection fixture configuration, the inspection fixture can become an active component of the measurement system and should be investigated accordingly.

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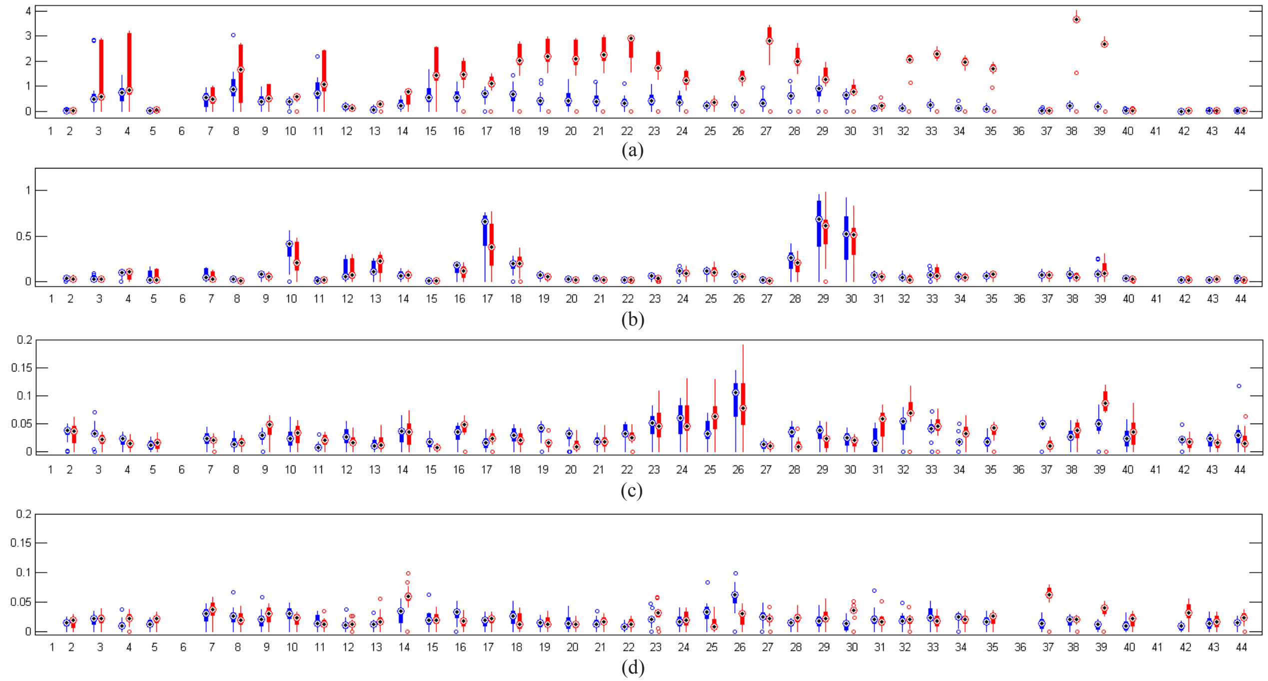

Fig. 5 Boxplot of measurements variability (in mm) of each positioning targets for the fixture configuration (a) I (b) II (c) III (d) IV and restraining sequence (1st seq in blue, 2end seq. in red). The variability where evaluated by using one of the 15 data sets as a reference (i.e. one part as ref. for each fixture configuration and restraining sequence).