Characterization and experimental evaluation of gear transmission errors in an industrial robot

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Characterization and experimental evaluation of gear transmission errors in an industrial robot

Abstract

Purpose – This paper proposes a simple technique for assessing the effect of gear transmission errors in a six-axis industrial serial robot, as these errors can vitally affect the industrial robot’s positioning accuracy.

Design/methodology/approach – The experimental procedure is developed using a laser interferometer system to measure bidirectional linear position errors for an ABB IRB 1600 industrial robot. A simple technique based on Fast Fourier Transformation (FFT) analysis is devised and implemented for the characterization, evaluation, and quantification of gear transmission errors. Structural deformation and backlash error are also discussed.

Findings – We found that the major sources of error affecting the performance of the robot come from joints 2 and 3. We also found that eccentricity errors, structural deformations, and backlash are the most important sources of error affecting the accuracy and the repeatability of the industrial robot studied. Additional tests show that the robot’s first joint has relatively poor bidirectional repeatability.

Practical implications – The usefulness of a laser tracker (or any other large range portable 3D measurement system) is questionable for assessing—let alone analyzing in depth—the gear transmission errors of some of today’s industrial robots. We demonstrate in this paper that a laser interferometer system can successfully measure gear transmission errors very accurately. The proposed methodology is simple, efficient, and easy to use for the characterization and quantification of the errors.

Originality/value – This work is the first to detail the use of the laser interferometer system for the characterization of the gear transmission errors of an industrial robot. A methodology has been developed and implemented for very accurately quantifying the effects of gear transmission errors, structural deformations, and backlash. The proposed methodology greatly simplifies the measurement setup and accelerates error quantification.

Keywords – gear transmission errors, structural deformation, backlash, Fast Fourier Transformation, repeatability, laser interferometer.

Paper type – research

1 Introduction

The characterization and improvement of robot performance in terms of accuracy have become increasingly important in modern manufacturing, particularly in the aerospace sector. Robot performance varies significantly over time, especially if the robot has been transported or involved in a collision. Ideally, a robot’s accuracy should be assessed annually, and if it is found to be unsatisfactory, the robot should be calibrated.

The accuracy of an industrial robot is primarily affected by geometric errors caused by mechanical-geometrical imperfections, such as link parameter errors and non geometric errors caused by gravity, joint compliance, gear errors, and backlash (Whitney et al., 1986). Generally, gravitational loading causes structural deformation, which can occur not only as a result of the robot manipulating a heavy object, but also due to the links supporting their own weight (Judd et al., 1990). According to Shiakolas et al. (2002), the most significant effects on robot accuracy can be attributed to the robot links and the joint zero offset. Servos vibration and dynamic errors also affect the dynamic performance of the robot, especially at high TCP speeds (Slamani et al., 2012a), and thermal expansion can affect repeatability and accuracy considerably (Slamani et al. (2012b), but only when long periods of time are considered (e.g. several hours of operation after a cold start).
Most industrial robots use gearboxes to amplify the torques produced by their motors. However, the use of gears introduces nonlinearities into the operation of the drive system, which cannot be easily analyzed with existing techniques. These nonlinearities cause the response of the robot joint to differ from the response demanded by the joint controller (Dagalakis and Myers, 1985). Gears also exhibit backlash, which is one of the most important factors affecting the repeatability of industrial robots (Slamani et al., 2012c). Bidirectional repeatability is important whenever a robot is sent to either manually taught configurations or configurations that are calculated online (e.g. using a camera or a touch probe). This is often the most serious problem associated with geared transmissions. Although required for proper tooth action, too much backlash may lead to unacceptable robot repeatability. Consequently, backlash effects should be checked frequently, using techniques devised for measuring and identifying them. Unfortunately, nonlinearities and backlash are not the only phenomena exhibited by gears that are not ideal. There are four other error sources that deserve mention. These are: eccentricity (radial run-out), orientation (axial run-out, or wobble), tooth-to-tooth contact, and tooth profile (Judd et al., 1990). Burisch and Raatz (2011) presented a method for compensation of the transmission error of micro harmonic drive gears for miniaturized robots. Measurement data of the transmission error were mathematically transformed into the frequency domain and filtered to the most important frequency modes of the function. These modes were used to build up a simplified mathematic model of the gear transmission error.

Generally, in a gear transmission system, the low frequency components (smooth variations) are mostly subject to eccentricity (run-out), undulation in the bearings guideways, and misalignment of the gears (orientation error). The high frequency components (sharp variations) are principally subject to tooth-to-tooth contact and errors caused by the ball bearings.

Robot performance can be improved by using either direct-drive motors (as in some SCARA robots) or high precision gear trains, characterized by very small backlash, high efficiency, low inertia, low friction, high stiffness, and low weight; or by placing high-resolution encoders at the output of the gear trains. However, these solutions cannot be applied simultaneously, and would raise the manufacturing cost of an industrial robot considerably.

On virtually all six-axis serial industrial robots, encoders with a typical resolution of $0.01^\circ$ are placed on the shafts of the motors, and gear reduction ratios of at least 100 are generally used for the first joints. It is clear, therefore, that the unidirectional repeatability of these robots is primarily affected by lost motion (hysteresis, backlash, and torsional elasticity) and friction in the gear trains, and only slightly influenced by the limited resolution of the encoder.

Numerous techniques have already been introduced for measuring and assessing the positioning performance of industrial robots. Aiguo et al. (2001), proposed a method for measuring the angle transmission error in both clockwise and counterclockwise directions. This method has been applied to the testing process in the production line of gear reducers for robots. Bréthé et al. (2006) used a triad of digital indicators, each with an accuracy of 3 μm, to measure and model the position repeatability of an old KUKA IR 364 industrial robot at several locations, and found it to be less than 36 μm. In her Ph.D. thesis, Eastwood (2004), and in related publications such as (Eastwood and Webb, 2009), a triad of digital indicators was used to evaluate the impact of various sources of error in a Tricept parallel robot, and she proposes compensation strategies for some of these errors. This work is very comprehensive in terms of analyzing the various sources of error, but pays little attention to the choice of measurement equipment and to the various performance criteria that can be used to represent the positioning performance of a robot.
Muelaner et al. (2010) used a FARO laser tracker to assess the repeatability of a large KUKA KR 240 industrial serial robot, and found that it is no more than 10 μm, when short periods of time are considered. The validity of such results is questionable, however, since the repeatability of the FARO laser tracker itself (ADM only), in a controlled environment, is approximately 8 μm at two meters. Indeed, to analyze the repeatability of today’s industrial robots, it is imperative to use high precision measurement equipment with an accuracy in the order of 1 μm, such as a telescopic ballbar or a laser interferometer.

Because of its simplicity and accuracy, the telescopic ballbar system is expected to become widely used and make a significant contribution to the performance assessment of industrial robots. Oh (2011a) proposes a technique for the detailed investigation of angular joint errors using a reference encoder combined with a precision electronic level and autocollimator. He also took circle contouring measurements using a telescopic ballbar to assess the significance of multi-axis movements on the accuracy of the end effector. Slamani et al. (2012b) used the telescopic ballbar measurement instrument to assess the accuracy and repeatability of a six-axis industrial serial robot. Furthermore, an empirical dynamic model was developed to predict the servo dynamic errors based circular tests with a ballbar (Slamani et al., 2012c). Oh (2011b) proposes a technique for characterizing the robot error in terms of datum location error and backlash error based on some of these ballbar tests. His experimental investigation showed that significant error components result from datum location error. Unfortunately, the method proposed by Oh (2011b) is not very practical, as it is time consuming, demands fine adjustment of the ballbar during the tests, and requires a robot model to analyze the results.

In fact, there may be some disadvantages to using the telescopic ballbar for assessing the performance of industrial robots. For example, the measuring range is a mere ±1.0 mm (in the case of the Renishaw telescopic ballbar, which is most popular commercial model), which is too small for most non calibrated industrial robots. Furthermore, the telescopic ballbar can only be used to measure the radial error. On top of that, the software that comes with the Renishaw wireless (Bluetooth) ballbar is specifically developed for use on a machine in which the circular motion is generated by the simultaneous movement of two orthogonal linear axes, and so a defined test sequence should be followed.

Today, the laser interferometer measurement instrument is a standard tool for accuracy assessment and the calibration of machine tools (Slamani et al., 2010) and coordinate measuring machines (CMMs), however, with the exception of a few papers (Slamani et al., 2012b; Slamani et al., 2012c; Young and Pickin, 2000), its use in industrial serial robots remains very limited.

In this paper, we explore the use of a laser interferometer system to measure and quantify gear transmission errors and assess the positioning performance of an ABB IRB 1600 industrial robot. Subsequently, the degree of influence of each error source on the accuracy and repeatability of the robot is evaluated and discussed.

2 Experimental procedures
Tests were performed on an ABB IRB 1600-6/1.45 industrial robot installed in a laboratory facility. The robot was manufactured in 2008 and has never been in a collision accident. It has neither the Absolute Accuracy option (i.e. it is not calibrated) nor the Advanced Shape Tuning option (for compensating the effects of friction at low speeds). A multi-purpose end effector (readily visible in Fig. 1) was used to mount the optics of the laser interferometer system. The weight of the end effector in the linear position error setup is 2.23 kg.
The measurement instrument used in this study is the latest model of Renishaw’s laser interferometer system. It is composed of an XL-80 laser unit, a XC-80 environmental compensation unit with external sensors, and measurement optics. The XL-80 laser unit and relevant optics installed in a setup for measuring linear position errors along a horizontal linear path is shown in Fig. 1. The XC-80 compensation system (attached to the steel table, as shown in Fig. 1) very accurately measures air temperature, air pressure, and relative humidity, and so compensates for the wavelength of the laser beam. As a result, the laser interferometer system has an accuracy of ±0.5 µm and a resolution of 1 nm within a range of 1 m.

The robot was programmed to move along a linear path, parallel to the Y axis of the robot base frame as shown in Figs. 2 and 3. The position component of pose $P_0$ (start pose) is \{1000 mm, 500 mm, 600 mm\} with respect to the robot base frame. The path is 1000 mm long and is uniformly divided into 1000 segments. The robot is programmed to move in linear bidirectional mode by starting 5 mm before reaching pose $P_0$ (and along the linear path) and stopping at $P_0$, then at each of the 998 intermediate poses, and finally at the end of the path. At the end of the path, the software reverses the robot’s direction of travel and stops the end effector at the same nominal points of measurement. A 5 mm overrun distance ensures that the first and last targets of a run are taken in the correct direction. The positive (forward) and negative (backward) motion directions enable the evaluation of the backlash error. The sequence is repeated five times, and a pause of 5 s is set, to allow full stabilization at each of the 1000 measurement poses before a measurement is taken.

Two additional, but slightly different tests were performed. In the first, only joint 1 of the robot rotates, slightly, in both directions, starting from a configuration where the robot is fully stretched and horizontal ($\theta_1 = 30.5^\circ \pm 2.23^\circ$, $\theta_2 = 90^\circ$, $\theta_3 = -90^\circ$, $\theta_4 = 0^\circ$, $\theta_5 = 0^\circ$, $\theta_6 = 0^\circ$). In the second test, only joint 3 rotates, again slightly, in both directions, starting from nearly the same configuration as in the previous test ($\theta_1 = 30^\circ$, $\theta_2 = 90^\circ$, $\theta_3 = -92^\circ \pm 2.85^\circ$, $\theta_4 = 0^\circ$, $\theta_5 = 0^\circ$, $\theta_6 = 0^\circ$).

It is known that in laser interferometer tests, when there is a significant separation between the optics at the datum position (i.e. $P_0$), a dead-path error occurs. To minimize potential dead-path errors associated with datuming, the optics were positioned close together, within 20 mm of one another when the laser is datumed (Fig. 1).

All the tests were performed at an ambient temperature between 21.43°C and 23.53°C.

3 Results and discussion
In accordance with ISO 9283:1998, accuracy is defined in this paper simply as:

$$ AP_q = \bar{q} - q_c, $$

where $q_c$ is the desired (command) coordinate (a distance) and $\bar{q}$ is the arithmetic mean of the $n$ measured coordinates ($q_1$, $q_2$, …, $q_n$). Similarly, unidirectional repeatability is defined in this paper as:

$$ RP_q = \pm 3S_q = \pm 3\sqrt{\frac{\sum_{i=1}^{n}(q_i - \bar{q})^2}{n-1}}. $$

Unidirectional repeatability refers to the repeatability at a pose when the arrival at that pose is from the same direction. It does not take into account the effects of backlash. Good
bidirectional repeatability is typically more difficult to achieve than unidirectional repeatability, precisely because industrial robots have to deal with backlash. In spite of its importance, bidirectional repeatability is never specified by the manufacturers of industrial robots, nor is it described in the ISO 9283:1998 guide, and it is rarely the object of performance assessments.

Backlash is defined as a component of bidirectional repeatability, and bidirectional repeatability is evaluated according to ISO 230-2 for machine tools as follows:

$$R_i = \max \left(3\sigma_i^\uparrow + 3\sigma_i^\downarrow + |\overline{B_i}|, 6\sigma_i^\uparrow, 6\sigma_i^\downarrow \right),$$

(3)

where $\overline{B_i}$ is the mean of the $m$ measurements of the backlash for pose $i$, defined as

$$\overline{B_i} = \overline{q_i^\uparrow} - \overline{q_i^\downarrow},$$

(4)

and $\overline{q_i^\uparrow}$ and $\overline{q_i^\downarrow}$ are the mean position errors for pose $i$ for the forward and backward direction respectively.

The tests for assessing gear transmission errors and backlash were undertaken in bidirectional mode. Figure 4 shows the graph of bidirectional linear position errors along the 1-meter path parallel to the base Y axis. It can be seen quite clearly from these plots that the magnitude of the progressive component of the position error for both the forward and backward directions increases gradually, cyclically, and negatively, up to about the 300 mm position, reaching an error of $-220 \, \mu m$ and $-150 \, \mu m$ for the forward and backward direction respectively. From this point, the progressive component of the position error increases, also cyclically but this time positively, reaching an error of $180 \, \mu m$ and $225 \, \mu m$ at the end of the travel for forward and backward direction respectively. We can also observe sharp cyclic errors affecting the accuracy of the robot.

As can be seen from Fig. 4, the robot has good unidirectional repeatability. The latter ranges between $5 \, \mu m$ and $34 \, \mu m$ for the forward direction and $8 \, \mu m$ and $25 \, \mu m$ for backward direction. In contrast, results show that the bidirectional repeatability (i.e. $R_i$) is strongly affected by the backlash. The bidirectional repeatability ranges between $52 \, \mu m$ and $148 \, \mu m$.

Figure 5 shows the mean for the five repetitions in both directions, as well as the backlash. From this figure, it is clear that the backlash is highly dependent on the robot configuration and is maximal in the middle of the path (near to the home position). This is probably because the home position is the most visited location and is more affected by wear.

Figure 6 shows another way of looking at the results presented in Fig. 4. We have basically taken the curves for the forward direction in Fig. 4 and “folded” them at the nominal position of 500 mm. In the first part of the curves (in blue), joint 2 rotates in the negative direction and joint 3 in the positive, while in the second part (in black), joints 2 and 3 follow exactly the reverse motion (see Fig. 7). We can observe in Fig. 6 that the two sets of curves have similar overall shapes (smooth variations). This behavior is therefore strongly related to the gear errors in joints 2 and 3.

During this first test, almost all the joints rotate (see Fig. 7) and more than 25 gears are involved (see Table 1). Table 1 presents the numbers of teeth for each gear and the gear ratios for the different joints of the IRB 1600 robot. Because each gear has its own specific characteristics, it also produces specific signals. As a result, the measured trajectory will suffer from a major source of error with different shapes and frequencies. Furthermore, if the signals overlap significantly and are contaminated with random noise, the situation becomes more complicated,
and at this point it is very difficult to identify the frequency components by looking at the original signal (Fig. 4).

In engineering practice signals are usually not described by mathematical functions but come from measurements acquired with a selected sampling interval $\Delta t$ (its inverse is the sampling frequency or rate $f_s$). The transmission error itself is a continuous function. However, due to the fact that the error is measured by a laser interferometer in static mode, it is mathematically described as a discrete function. In order to characterize and simplify the transmission error, it has to be transformed into the spatial frequency domain, so that only the main spatial frequency modes can be considered. Fast Fourier Transformation (FFT) is a powerful technique commonly used in signal analysis for detecting periodicity and obtaining the frequency components of a signal buried in a noise.

After the linear position error in relation to distance is recorded with the laser interferometer, the Fourier transformation is carried out by employing an FFT analyzer (Fig. 3). To assess the contribution of the second and third joints, the FFT is first applied against the first 500 mm of one of the measured data of the forward direction presented in Fig. 6 (see Fig. 8a). The overview of the proposed method to assess the gear transmission errors in a six-axis industrial serial robot is summarized in Fig. 3.

A closer look at the FFT result in Fig. 8b shows that the most distinguishable transmission error component is at 0.36 cycles/degree. Because joint 2 rotates 7.3° during the 500 mm path and then turns back, the 0.36 cycles/degree shown in Fig. 8b is equivalent to 2.6 cycles per 500 mm path. This is equal to the amount of transmission error of joint 2 shown in Table 2. The 0.66 cycles/degree is contributed by joint 3, and is equivalent to 4.8 cycles per 500 mm (per 14.6°), as shown in Table 2.

As mentioned above, all the joints rotate simultaneously during the first test. Joint 1 rotates about 56.3° in one direction only, joint 2 rotates 7.3° back and forth, joint 3 rotates 14.6° back and forth, joint 4 rotates 76.6°, joint 5 rotates only 0.57° back and forth, and joint 6 rotates 54.2°, as shown in Table 2 and Fig. 7. Table 2 also shows the number of cycles/m due to the eccentricity of the first gear in each train, obtained using the following formula:

$$E_e = \frac{R_i \theta_i}{360^\circ}, \quad (5)$$

where $E_e$ is the eccentricity error in cycles/m, $\theta_i$ is the rotation angle (in degrees) of joint $i$ during the test with 1 meter of linear travel, and $R_i$ is the gear ratio of joint $i$:

$$R_i = \frac{Z_{i,2} Z_{i,4} \ldots Z_{i,2n}}{Z_{i,1} Z_{i,3} \ldots Z_{i,(2n-1)}}, \quad (6)$$

where $Z_{i,j}$ ($j = 1, 2, \ldots, 2n$) is the number of teeth in gear $j$.

The tooth-to-tooth error is calculated as follows:

$$t_e = \frac{Z_{i,2n} \theta_i}{360^\circ}, \quad (7)$$

where $t_e$ is the tooth-to-tooth error in cycles/m, and $Z_{i,2n}$ is the number of teeth in the last gear in the gear train of joint $i$. 


With eccentricity error, each cycle corresponds to a complete revolution of the gear. In other words, gear eccentricity in the first gear of a gear train induces disturbances with a period equal to one revolution.

Figure 10 shows a partial zoom of Fig. 9b. The most distinguishable transmission error components are at 6.7 cycles/m and 13 cycles/m. These most probably correspond to the eccentricity errors associated with the first gear of joints 6 and 4 respectively, which are at exactly 12.7 cycles/m and 6.6 cycles/m (Table 2).

With tooth-to-tooth error, each cycle corresponds to the angular separation between successive gear teeth. In other words, tooth-to-tooth error induces disturbances with a fundamental frequency equal to the number of teeth per revolution (Eq. 7).

The transmission error component of 21 cycles/m is caused by the eccentricity errors associated with the first gear of joint 1 (20.32 cycles/m in Table 2) and/or the tooth-to-tooth errors of the last gear of joint 1 (20.17 cycles/m in Table 2). The 9.7 cycles/m and 23.5 cycles/m peaks correspond to tooth-to-tooth errors of the last gear of joints 3 (4.86×2 in Table 2) and 4 (23.41 in Table 2) respectively.

In order to simplify the analysis and gather more information about the transmission error components, additional tests were carried out with joint 1 and joint 3. Figure 11 shows the graph of the recorded results of the bidirectional linear position errors when only joint 1 rotates, a total of 4.46°. Note that this is the maximum range at which the linear component of the circular displacement of the end effector can be measured using the laser interferometer.

Results show that the unidirectional repeatability ranges between 33 µm and 64 µm for the forward direction, and 24 µm and 47 µm for the backward direction. In contrast, results show that the bidirectional repeatability is strongly affected by the backlash. The bidirectional repeatability ranges from 82 µm to 143 µm. This poor bidirectional repeatability can be explained by the fact that in our lab the robot frequently turns around axis 1. This means that the first joint is mostly excited and as consequence is more affected by wear. This leads to apparition of backlash and worse bidirectional repeatability. As shown in Fig. 12, the backlash in joint 1 is about 30 µm. However, we can visually observe in Fig. 10 that the most distinguishable transmission error component is 3 cycles for 4.45°, or approximately 0.7 cycles/degree. This corresponds to the peak of 0.7 cycles/degree in the FFT graphs in Fig. 13. We can conclude from this test that joint 1 gives a transmission error of about 0.7 cycles/degree. In the test of 1 meter travel, joint 1 rotates a total of 56.3° degrees, which means that it produces a transmission error of 39.4 cycles/m (56.3×0.7), which in turn means that the peak of 39 cycles/m in the FFT graph in Fig. 10 is contributed by joint 1.

Figure 14 shows a graph of the recorded results of the bidirectional linear position errors when only joint 3 rotates, a total of 5.6°. Results show that this joint is more repeatable than joint 1. The unidirectional repeatability ranges between 6 µm and 16 µm for the forward direction and 8 µm and 16 µm for the backward direction. As shown in Fig. 15, the backlash is three times smaller than that of joint 1, and is only about 12 µm. As a result, the bidirectional repeatability is much better; varying between 27 µm and 41 µm. Figure 16 shows a plot of the FFT against measured data shown in Fig. 14. Finally, Fig. 16 shows that the most distinguishable transmission error components are at 0.6 cycles/degree and 0.9 cycles/degree. If we project this information to the 1 meter tests, we can have transmission errors of 17.52 cycles/m (14.6×2×0.6) and 26.28 cycles/m (14.6×2×0.9). These correspond to peaks of 17.6 cycles/m and 26 cycles/m respectively in the FFT results (Fig. 10).
According to Figs. 10 and 13, the 20.16 tooth engagements of the last gear of joint 1 give peaks at frequencies of 21 cycles/m and 39 cycles/m. By a simple analysis, we can conclude that from 23.5 teeth engaged of the last gear of joint 4, we can have peaks at frequencies around 23.5 cycles/m and 43 cycles/m (Fig. 10).

This procedure allows extremely accurate diagnosis of gear errors, which makes it possible for the robot builder to determine whether the robot is in good or bad mechanical condition. If the mechanical condition is bad, then the proposed method makes it possible to determine the cause of the problem. This technique can also be used by the robot user in conjunction with predictive maintenance, that is, maintenance of robots based on an indication that a problem is about to occur. The early detection of faults in a robot can be made successfully only by comparison with a reference spectrum. This method can also find wide applications in the domain of micro assembly processes with miniaturized robots, were good repeatability and high accuracy are required.

4 Conclusions

A laser interferometer-based technique has been devised for measuring the position errors of a six-axis non calibrated ABB IRB 1600 industrial robot and assessing its performance. This technique not only provides a convenient and accurate method of measuring position errors, but also offers several other useful measuring capabilities. For example, the ability to measure backlash and transmission error continuously and accurately is unique and very valuable in certain applications. Furthermore, an approach is presented to quantify the relative contributions of gear transmission errors based on Fast Fourier Transformation analysis on the spatial frequency domain. FFT analysis shows a large number of peaks corresponding to eccentricity errors and tooth-to-tooth errors of gears of the transmission system of the robot tested. Structural deformation and backlash are also investigated in this work. Results show that the highest percentage of errors comes from joints 2 and 3. These joints cause eccentricity errors and a large structural deformation. Results also show that the backlash can dramatically affect the accuracy and bidirectional repeatability of the robot studied. Additional tests on joints 1 and 3 showed that the first joint has the worst bidirectional repeatability.

Acknowledgments

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References


Figure 1: Laser interferometer setup for measuring linear position errors along a linear path parallel to the Y-axis of the base frame of the IRB 1600 robot

Figure 2: Schematic showing the linear path analyzed with the laser interferometer
Figure 3: Overview of the method for assessing the gear transmission errors in a six-axis industrial serial robot.

Figure 4: Linear bidirectional position errors along the path parallel to the Y-axis.
Figure 5: Backlash errors along the path parallel to the Y-axis

Figure 6: Linear position errors along the path parallel to the Y-axis for the forward direction
**Figure 7:** Programmed joint angles as function of programmed nominal position

**Figure 8:** FFT performed on the first signal of the forward direction for the first 500 mm
Figure 9: FFT performed on the first signal of the forward direction for 1 meter travel

Figure 10: A partial zoom of Fig. 9b
**Figure 11:** Linear bidirectional position errors when only joint 1 rotates

**Figure 12:** Backlash error when only joint 1 rotates
Figure 13: FFT performed on the first signal of the forward direction presented in Fig. 11.

Figure 14: Linear bidirectional position errors when only joint 1 rotates.
**Figure 15:** Backlash error when only joint 3 rotates

**Figure 16:** FFT performed on the first signal of the forward direction presented in Fig. 14
**Table 1**: Numbers of teeth in each gear of the gear trains in the IRB 1600 robot

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<th>Joint</th>
<th>$Z_{i,1}$</th>
<th>$Z_{i,2}$</th>
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<th>$Z_{i,4}$</th>
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**Table 2**: Analysis of the eccentricity and tooth-to-tooth error for the various joints of IRB1600 for the 1 meter test

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<td>Joint travel [degrees]</td>
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<td>20.17</td>
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Response to the Reviewers’ Comments

We thank the editor and the anonymous reviewers. We have carefully revised our paper by responding to the comments of the reviewers and making additional modifications. All additions and modifications in our paper have been highlighted in yellow. In what follows, the comments of the reviewers are indented and in smaller font.

Reviewer 1

Comments:
A good well written paper that with a few minor improvements will make a good contribution to the field. Addition of a figure showing the robot path used for the measurements, more descriptive titles for the figures, an attempt to explain why some of the findings occur and more analysis of harmonics that could be caused by other gears in the drive mechanism.

This has been done.

Additional Questions:
1. Originality: Does the paper contain new and significant information adequate to justify publication?: The paper contains new and significant information relating to harmonic errors in industrial robots caused by gear errors.

2. Relationship to Literature: Does the paper demonstrate an adequate understanding of the relevant literature in the field and cite an appropriate range of literature sources? Is any significant work ignored?: The paper appropriately references a wide range of literature and all of the highly relevant work to this area that I am aware of.

3. Methodology: Is the paper's argument built on an appropriate base of theory, concepts, or other ideas? Has the research or equivalent intellectual work on which the paper is based been well designed? Are the methods employed appropriate?: The work is soundly based and the experiments and measurement systems well designed.

4. Results: Are results presented clearly and analysed appropriately? Do the conclusions adequately tie together the other elements of the paper?: The results are reasonably clear and the analysis appropriate. The presentation could be improved however by improved titles for the figures (many state 'one signal of' why does it not state which signal?) and inclusion of a diagram showing where the robot path used fits relative to the robot's working envelope.

The titles for the figures in question have been improved. A schematic showing the linear path on the robot’s working envelope has been added in the paper (Fig. 2).

5. Practicality and/or Research implications: Does the paper identify clearly any implications for practice and/or further research? Are these implications consistent with the findings and conclusions of the paper?: There is little discussion of what the implications for practice are beyond stating that it can be used to judge the condition of a robot. There are also some conclusions drawn with no attempt to answer why? (e.g. 'the first joint has the worst bidirectional repeatability') Some discussion of these would add to the paper.

This has been done in Section 3.

6. Quality of Communication: Does the paper clearly express its case, measured against the technical language of the field and the expected knowledge of the journal's readership? Has attention been paid to the clarity of expression and readability, such as sentence structure, jargon use, acronyms, etc.: The paper is generally very well written and easy to read and understand. It is highly appropriate for the journal's readership.
Reviewer 2

Comments:
In the paper, the laser interferometer device is employed to identify the gear transmission errors of an industrial robot. The research is valuable and relatively new. However, the author failed to propose the methodology, so the current work is not suitable to be published.

To better explain the proposed methodology, an overview of the method used to assess the gear transmission errors in a six-axis industrial serial robot has been added in the paper (Fig. 3).

Additional Questions:
1. Originality: Does the paper contain new and significant information adequate to justify publication?: In the paper, the laser interferometer device is employed to identify the gear transmission errors of an industrial robot. The research is valuable. However, the current work is not new enough to be published.

2. Relationship to Literature: Does the paper demonstrate an adequate understanding of the relevant literature in the field and cite an appropriate range of literature sources? Is any significant work ignored?: Yes, some new developments should be summarized for improvement.

We now cite new references in Section 1.

3. Methodology: Is the paper's argument built on an appropriate base of theory, concepts, or other ideas? Has the research or equivalent intellectual work on which the paper is based been well designed? Are the methods employed appropriate?: In the paper, the laser interferometer device is employed to identify the gear transmission errors of an industrial robot. Some simple experiments are given and discussed. However, the author failed to propose the methodology to verify its effectiveness.

As already mentioned, an overview of the method used to assess the gear transmission errors in a six-axis industrial serial robot has been added in the paper (Fig. 3).

4. Results: Are results presented clearly and analyzed appropriately? Do the conclusions adequately tie together the other elements of the paper?: The laser interferometer device is employed to identify the gear transmission errors and demonstrated on the ABB IRB1600 industrial robot. The results are discussed based on a linear path of end effector and rotation of joint 1 and joint 3. Some questions are below:

1) The robot is uncalibrated, how can the robot end effector move along a linear path?

Most industrial robots, when not calibrated, deviate no more than 2 mm from a linear path (see Young et al., 2000). Even if that error were 3 mm, that would still be sufficient to allow the use of a laser interferometer (Young et al., 2000; Slamani et al., 2012b). When the deviation becomes larger, the signal strength on the screen of the laser interferometer software decreases progressively until the signal is completely lost.

In our tests, the signal strength displayed on the laser interferometer software was 100% during the measurement, over the entire path.

2) Even the robot is calibrated, how to identify the errors of end effector what sources caused? How to separate them?

The error separation technique is widely adopted for many machine tool performance tests. This paper is focused on identifying and separation gear transmission error (periodic errors) for an ABB IRB 1600 industrial serial robot. The error separation technique proposed in this work is based on Fast Fourier Transformations (FFT), a well-known method that is commonly used in signal analysis for detecting periodicity.
3) What is the methodology to prove the experiment?
In the paper, we described a methodology for the identification of periodic errors due to gear transmission errors using FFT. The overall methodology is depicted in Fig. 3.

4) Furthermore, it is better give a known method to verify the truth of the experiments conducted on the robot.
Despite its importance, the measurement of the gear transmission error on industrial robots is not described in the ISO 9283:1998 guide, and it is rarely the object of performance assessments. Thus, there is no known method to accurately verify the effect of the gear transmission errors on industrial robots. We have therefore devised a new method to identify the gear transmission errors using laser interferometer measurements and based on ISO 230-2, which is widely used for the performance assessment of machine tools.

5. Practicality and/or Research implications: Does the paper identify clearly any implications for practice and/or further research? Are these implications consistent with the findings and conclusions of the paper?: OK

6. Quality of Communication: Does the paper clearly express its case, measured against the technical language of the field and the expected knowledge of the journal's readership? Has attention been paid to the clarity of expression and readability, such as sentence structure, jargon use, acronyms, etc.: Not enough

Our first manuscript was revised by a professional corrector. Nevertheless, we have tried to improve our second manuscript.

Reviewer 3
Comments:
Explain configuration and joint mechanism of ABB Robot which you tested
We have done this by adding Fig. 2.

Page 5
Line 29: need more explanation “the backlash maximal in the middle of path”
This has been done.

Line 49-52: need more detailed explanation, it is difficult to understand
This too has been done.

Explain relationship between FFT analyzer and passion error of interferometer.
There is no relationship between the FFT analyzer and the accuracy of our laser interferometer. The laser interferometer has a linear measurement accuracy of ±0.5 ppm and a linear resolution of 1 nm. Furthermore, the XC-80 compensation system (attached to the steel table, as shown in Fig. 1) very accurately measures air temperature, air pressure, and relative humidity, and so compensates for the wavelength of the laser beam. Thus, the measurement noise is negligible compared to the position errors of the robot. In fact, the laser interferometer is used to assess the accuracy of machines that are way more accurate than industrial robots, such as coordinate measuring machine (CMMs) and machine tools.

Additional Questions:
1. Originality: Does the paper contain new and significant information adequate to justify publication?: This paper has originality
2. Relationship to Literature: Does the paper demonstrate an adequate understanding of the relevant literature in the field and cite an appropriate range of literature sources? Is any significant work ignored?:

3. Methodology: Is the paper's argument built on an appropriate base of theory, concepts, or other ideas? Has the research or equivalent intellectual work on which the paper is based been well designed? Are the methods employed appropriate?:

4. Results: Are results presented clearly and analysed appropriately? Do the conclusions adequately tie together the other elements of the paper?:

5. Practicality and/or Research implications: Does the paper identify clearly any implications for practice and/or further research? Are these implications consistent with the findings and conclusions of the paper?:

6. Quality of Communication: Does the paper clearly express its case, measured against the technical language of the field and the expected knowledge of the journal's readership? Has attention been paid to the clarity of expression and readability, such as sentence structure, jargon use, acronyms, etc.:

Reviewer 4
Comments:
Since the paper says that laser rangefinders are not good enough, it would be good if their accuracy were quoted for comparison. Also, it would be useful to compare the deviations shown here to deflections caused by typical payloads. I suspect that payloads of several kg would produce deflections of similar magnitude.

A comparison between laser trackers, laser interferometer systems and telescopic ballbars for assessing the positioning performance of industrial robots is given in (Slamani et al. 2012b).

Additional tests were performed with payloads of 2.3 kg and 6 kg along a path of 1000 mm. The path is divided uniformly into four segments (see the figure below). Results show that the deflection increases linearly with position and reaches the worst value (45 µm) at the end of travel, where the robot is most stretched. We can conclude from this that axes 2 and 3, under the gravitational effect, are those most responsible for the robot deflection.

Figure: Linear position errors at five poses along the path parallel to the base Y-axis with payload of 2.3 kg and 6 kg.
Additional Questions:
1. Originality: Does the paper contain new and significant information adequate to justify publication?: Yes
2. Relationship to Literature: Does the paper demonstrate an adequate understanding of the relevant literature in the field and cite an appropriate range of literature sources? Is any significant work ignored?: Yes
3. Methodology: Is the paper's argument built on an appropriate base of theory, concepts, or other ideas? Has the research or equivalent intellectual work on which the paper is based been well designed? Are the methods employed appropriate?: Yes
4. Results: Are results presented clearly and analysed appropriately? Do the conclusions adequately tie together the other elements of the paper?: Yes
5. Practicality and/or Research implications: Does the paper identify clearly any implications for practice and/or further research? Are these implications consistent with the findings and conclusions of the paper?: Yes
6. Quality of Communication: Does the paper clearly express its case, measured against the technical language of the field and the expected knowledge of the journal's readership? Has attention been paid to the clarity of expression and readability, such as sentence structure, jargon use, acronyms, etc.: Yes