Status check and calibration method for robot ABB IRB 140

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Abstract. The paper presents a method to evaluate the status of an industrial robot (IR) model (ABB IRB 140) in terms of positioning accuracy and repeatability and a method of calibrating this robot using the ABB pendulum kit. These methods are required after servicing the robot, or if the robot's batteries have been discharged or changed. In these cases, classical software calibration is no longer sufficient because the encoder positions are lost. This issue can be solved only using the pendulum calibration kit (or similar systems such as ABB's newest "axis calibration kit").

1. Introduction
To maintain their accuracy, industrial robots must be recalibrated periodically. For IR, there are many calibration methods but typically divided into 2 categories: easy software calibration (using only the teach-pendant or programming software) and calibration requiring external kits or elements (such as a calibration method using calibration pendulum). This paper discusses the second category, more precisely that one involving the use of the pendulum kit [1]. Such a calibration method is required in the following cases: when parts related to robot calibration positions have been changed or serviced, when the robot's batteries have been discharged or changed, if resolver errors occurred, if a signal between the resolver and the measurement board was interrupted or if the robot's axes were moved while the control system was disconnected, as well as previously to an evaluation of absolute accuracy of the robot by experimental methods need to be performed. Such problems of the robot are hard to notice especially, as will be seen in the experimental results, because IR's repeatability may remain in very good parameters even if positioning errors are extremely high. To carry out the measurements to determine the state of the robot before and after the calibration, in this case, a laser-tracker system was used following the position of the end-effector in various programmed positions of the robot. By comparison of the programmed positions and the real positions measured with the laser tracker the state of the robot was determined.

2. The studied robot
The robot from the laboratory on which the measurements were made is an ABB IRB 140 model [2]. It is a 6 DOF articulated arm robot with an asymmetrical structure. Before being installed in the faculty lab, this robot was mainly used as a test and training robot. Over time (since 2007), the robot has been transported tens of times to different locations where tests or trainings have been done. He suffered strikes and was serviced multiple times. From the information that can be read on his teach-pendant, 986 hours have passed since the last service from which 658 hours of effective operation. The last work done on it was changing of the discharged batteries (1 week before the measurements). More robot specification can be found in Table 1 and Figure 1 below).
Table 1. Technical specifications of ABB IRB 140 robot [2]

| Main applications | Physical |
|-------------------|----------|
| part extraction of die-casting | Base dim. 400 x 450 mm |
| Specifications | Weight 98 kg |
| Max. payload 6 kg | Performances (ISO 9283) |
| Max. reach 0.81 m | Repeatability 0.03 mm (average from ISO tests) |
| Axes 6 | Accuracy between 0.35 and 0.8 mm |
| Protection IP 67 | Axis movement |
| Mounting: ground/suspended | A1 ±360°, 200°/s, A5 ±240°, 360°/s |
| Controller IRC5 | A2 ±200°, 200°/s, A6 ±800°, 450 °/s |
| P. Supply 200-600V,50/60Hz | A3 ±280°, 260°/s |
| Consumed power 0.44kW | A4 ± 400°, 360°/s |

Figure 1. ABB IRB 140 link dimensions [2]

3. Laser-tracker measurement system
In order to evaluate robot accuracy and repeatability a laser tracker measurement system was used. The measurement system is a RADIAN API laser tracker [7]. This laser-tracker system is a dynamic (continuous acquisition) measurement system that uses spherical mirror retro-reflectors (SMRs) to track the laser beam. It is based on a laser interferometer (IFM) system with the ability to measure unparalleled distances and has an “on-board reference” measurement technology. The operating and measurement principles for similar systems are presented in [3], [4], [5]. The laser tracker measurement system and its performance are shown below in Figures 2 and 3 and in Tables 2 and 3.

Figure 2. Radian laser-tracker and spherical reflector (SMR) [6]  Figure 3. Measurement accuracy of API Radian laser-tracker [7]
### Table 2. Laser-tracker specifications

| Specification               | Value                      |
|----------------------------|----------------------------|
| L1 (Diameter)              | 50 m (100 m)               |
| Azimuth range              | ±320°                      |
| Elevation range            | -59° to 79°                |
| 3D measurement performance|                           |
| Volumetric accuracy (IFM)  | ±10 µm + 5 µm/m*           |
| Axial angular accuracy     | 3.5 µm/m                   |
| Maximum angular speed      | 180°/sec                   |
| Maximum angular acceleration| 180°/sec²                 |

*Measurement of a Scalebar per ASME B89.4.19-2006

### Table 3. Measurement range

| Measurement Range     | Range | MPE  |
|-----------------------|-------|------|
| In-Line Distance Measurement |       |      |
| 2 to 5 m              | 0.002 mm  |
| 2 to 10 m             | 0.004 mm  |
| 2 to 20 m             | 0.009 mm  |
| 2 to 50 m             | 0.024 mm  |
| 2 to 80 m             | 0.039 mm  |
| Scale Bar Measurement |       |      |
| 2 m                   | 0.028 mm  |
| 5 m                   | 0.049 mm  |
| 10 m                  | 0.065 mm  |
| 20 m                  | 0.156 mm  |
| 50 m                  | 0.308 mm  |
| 80 m                  | 0.580 mm  |

4. Measurement procedure

Performance criteria for industrial robots are stated in the international standard ISO 9283 [8]. This standard defines performance parameters for robots and describes test methods for those parameters. Among performance characteristics of an IR this paper is referring only to pose accuracy and pose repeatability. To determine those two characteristics for an IR, the standard states that the measurements should be performed in a space called usually “ISO cube”. Such “ISO cube” measurements should be taken both in front of the robot and sideways, all the measurements being related to the same coordinate system (usually robot’s base).

Since our robot is implemented in a laboratory application and due to limitations of robot’s working range, measurement “ISO cubes” couldn’t be defined identical in front of the robot and in sides of the robot. The measurement targets were programmed in the following way: 45 equally spaced points (150 mm between) in a cube placed in front of the robot with linear trajectories between them and 27 equally spaced points (150 mm between) in a cube placed in the right side of the robot also with linear trajectories between them. In the following figures 4 and 5 the real robot and surrounding environment from our lab is presented and the targets and trajectories programmed via official Programming and Simulation software ABB Robot Studio.

![Figure 4. IR ABB IRB 140 in faculty laboratory](image1)

![Figure 5. Targets and trajectories](image2)
For the measurements necessary to determine the robot’s accuracy all trajectories between targets were programmed using MoveL function (linear movement in Rapid programming) in conformity with standard specifications. Every measurement cycle starts from the bottom left target closest to the robot (both for the front cube as per side cube) and moves through all targets of the same vertical layer then it moves to the next one layer. Every time between the 2 successive measurements the robot is only moving in increments of 150 mm. Every point in each cube was measured 4 times, along identical positioning cycles with different positioning speed. The robot positioning measurement cycles where programmed at 10%, 20%, 40% and 60% of its maximum moving speed to observe the influence of robot speed on the robot’s positioning accuracy. Same measurement cycles were performed first with the robot in the initial status (before calibration) and then repeated after performing the calibration procedure.

For repeatability measurement evaluation, other movement cycles were programmed and complementary measurements have been done, a single target being measured (the target corresponds to the centre point of the front cube). To perform the repeatability measurement procedure the robot was programmed to continuously move along some paths (figure 6) involving the participation of all his joints in interpolating, for a specified number of cycles, all of them with end-return in the same target location and orientation, corresponding to the position point to be measured. This time, an increased number of measurements were performed at the 20%, 40% and 60% rates of maximum speed along 10, 20, and 30 sets of movement cycles. The different speed rates were used to observe their influence of robot's speed on its repeatability. It was also intended to identify if the number of cycles and the number of measurements have any influence too, so that is why for each speed rate were measured first 10 points (along 10 cycles of movement), then 20 and 30 points.

The red dot from figure 6 represents the target where robot’s position was measured to determine its repeatability (the centre of the front measurement cube). For repeatability evaluation traversing 10 times the complete trajectories showed in figure 6 represents 1 cycle of movement. After each movement cycle the robot goes into the measurement position and waits 10 seconds so that the target coordinates are registered by the laser tracker. This time the movement instructions of the robot were programmed using MoveJ function (joint movement). First the two circles from the front of the robot being completed then the other two from it’s side.

Figure 6. Robot’s path for each repeatability cycle

More of the measurement set-up is presented in the following figures.

Figure 7. Laser-tracker in home position, reflector mounted on the robot and robot in repeatability measurement position
5. Calibration procedure

Previously to use the industrial robot for performing certain tests, it was necessary to know exactly its state, in terms of its accuracy and its repeatability. Apparently, the robot worked smoothly but to identify also how accurate is moving the laser-tracker measurement system was necessary to put into operation. As result, even from the first tests, there were identified very large differences (in the order of millimetres) between the programmed points and the points physically reached by the robot. Thus, a first calibration procedure was attempted (from the user's menu accessed by the teach-pendant) but without solving the problem. Taking into account that the robot's batteries have been changed relatively recently, it was concluded that volatile memory was erased and robot's encoders from each numerically controlled axis have lost their zero position and have to be reset. However, resetting the zero position transducers to correct the zero set-up of each robot's NC axis requires the use of an external calibration kit based on a level meter equipment. After connecting this kit to the robot controller and the level meter is mounted in a dedicated place on the robot's structure the information supplied by an encoder related to current position and the effective (real) position of a mobile element may be read. Thus, the kit determines the differences between the coordinates values supplied of the transducer and the actual coordinates values identified by the level meter and allow performing multiple move commands on the axis for updating the position differences until the offset is removed. This is done axis by axis starting from the bottom side of the robot (axis 1) and ending with the 6th axis (end flange rotation axis). The pendulum kit components and connections with the robot controller are presented in figure 8 [1].

![Figure 8. ABB Calibration Pendulum Kit and Level meter 2000](image1)

![Figure 9. IRB 140 pendulum mounting positions (side and back)](image2)
Calibration of each axis must be done separately and successively. Many of ABB robots (including IRB 140) have dedicated markers and reference surfaces where the calibration pendulum must be mounted. Those areas are highlighted in the following figures (9 and 10) without and with the level meter mounted on.

For the calibration procedure it is necessary to set up the robot in the “home” position (0° on all axes, figure 11). Once the pendulum kit is connected at the robot controller then the procedure must be lunched by using the teach-pendant. For this purpose, from ABB menu, first Program Editor is selected, then "test" is tapped and afterward Call routine and Call Pendulum routine are successively selected, finally followed by "go to" tapping. Afterwards the program may be start by pressing the start button and then instructions from the teach pendant must to be followed. After the calibration procedure is performed, the encoders can be updated from “MENU” and “CALIBRATION” menus using “UPDATE” option.

In “UPDATE” option encoders must be selected then the check-boxes corresponding to the desired axes should be checked (or much more easily it may be use the “select all” option). After these, by pressing update icon the encoder update procedure will start.

During the calibration procedure the robot starts to move many times and very slowly only from 1-st axis and at every move the encoders are updated by a small offset. The robot gradually corrects the values of the position transducer by amounts of 0.001° up to 0.0002°. Taking into account that the initial values of the encoders are written on a label located on the back side of the robot, after the calibration the new values set for them should be noted down and placed above the old values.

To be sure that the calibration procedure was successfully performed it is recommended to run the calibration “home position” twice and check if the values on the axes are really 0° and if the calibration marks are perfectly aligned.
The full procedure of robot calibration is described step by step in ABB’s “Calibration Pendulum operating Manual” [1].

6. Measurements and results

The measurements tests started with the accuracy tests and ended with the repeatability tests. For both the measurements were performed first at 10% of the robot’s full speed, which was progressively raised up to 40% and 60%. Each test was performed on different days to allow the robot to cool down and get the most accurate results. In same purpose the environment temperature of each day was monitored to be in similar limits.

The data acquisition was done using the “Tracker Cal” software which is necessary to operate and allows data acquisition from the laser tracker measurements. This whole system is continuously monitoring the target reflector’s position and can continuously record its current position. However, even the final target current position may be recorded almost at an instant, in our experiments the software was set to start up data acquisition only when the reflector still stays for at least 5 seconds in the final target point, (in every measurement point the robot being programmed to hold for 10 seconds to allow a generous stabilization time). The following figures depicts the robot in some of the measurement configurations.

As above was specified first of all the initial status of the robot was investigated by performing (previously of any calibration procedure) the positioning accuracy tests.

Even from the first measurements it was observed that there is something wrong. There were identified from measurements some abnormal positions with large errors even in the order of tens of millimetres from passing from a measurement point to a successive one. This was the clue that made us think that robot’s position transducers / encoders have lost their values and that the robot did not know anymore its joints current positions. However, the full set of measurements were performed with
the robot as it was. The values of the measurements for both states, uncalibrated and calibrated robot can be observed in following subchapters 6.1 and respectively 6.2.

6.1 Measurements of the uncalibrated robot
A complete set of measurements was performed before calibration at all robot speed settings for both precision and repeatability tests. The measured values are considered irrelevant as long as the robot did not really know what the real axes positions are so only the measurements made at 10% of the robot speed are presented only to show their magnitude when so cases of encoders de-calibration is happening.

6.1.1 Accuracy measurements of the uncalibrated robot
As it may be observed from the below graphs, the positioning errors are enormous versus the IR's manual specified limits (accuracy between 0.35 and 0.8 mm) and it is obviously that the resetting of the encoders values mandatory needed to be done.

![Figure 16. Accuracy measurement of the uncalibrated robot at 10% of maximum speed in FRONT CUBE](image1)

![Figure 17. Accuracy measurement of the uncalibrated robot at 10% of maximum speed in SIDE CUBE](image2)

6.1.2 Repeatability measurements of the uncalibrated robot
As can be seen from the graphs below, the repeatability values can be considered to be acceptable against the limits specified in the RI manual (0.03mm repeatability) even without resetting and recalibrating the transducers.
Figure 18. Repeatability test of the uncalibrated robot at 10% speed and 10 cycles

Figure 19. Repeatability test of the uncalibrated robot at 10% speed and 20 cycles

Figure 20. Repeatability test of the uncalibrated robot at 10% speed and 30 cycles
6.2 Measurements of the calibrated robot

The full set of measurements were performed also on the calibrated robot. Due to the large number of measurements and graphics resulted, in the followings it will be presented only the measurement results for 10% and 60% of speed leaving other observations about the other measurements to be made in the conclusions chapter.

6.2.1 Accuracy measurements of the calibrated robot

![Positioning accuracy - front - 10% (calibrated)](image1)

**Figure 21.** Accuracy test of the calibrated robot at 10% speed in FRONT CUBE

![Positioning accuracy - front - 60% (calibrated)](image2)

**Figure 22.** Accuracy test of the calibrated robot at 60% speed in FRONT CUBE
Figure 23. Accuracy test of the calibrated robot at 10% speed in SIDE CUBE

Figure 24. Accuracy test of the calibrated robot at 60% speed in SIDE CUBE

6.2.2 Repeatability measurements of the calibrated robot

Figure 25. Repeatability test of the calibrated robot at 10% and 10 cycles
Figure 26. Repeatability test of the calibrated robot at 10% and 30 cycles

Figure 27. Repeatability test of the calibrated robot at 60% and 10 cycles

Figure 28. Repeatability test of the calibrated robot at 60% and 30 cycles
7. Conclusions
The paper presented an experimental study where the evaluation of the absolute accuracy and repeatability of an ABB IRB 140 robot was investigated by using a laser-tracker system. By means of preliminary experimental results processing it was demonstrated that previously to evaluate the robot's absolute accuracy a precise robot's calibration procedure was necessary to be performed. Accordingly to this conclusion beside the method used for robot's accuracy evaluation, in the paper there was also presented a method of precise robot's calibration using a pendulum kit system, (performed previously to the final evaluation of the robot absolute accuracy). Conclusions in terms of robot's absolute accuracy and repeatability improvement and their dependence by robot TCP speed were also presented.

For the experimental data processing all errors were calculated by the equation of $\Delta P = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$ and then averaged for each measurement test.

In terms of final results obtained from the experimental works performed at different investigation stages following conclusions may be reached:
1. As the un-calibrated robot didn't effectively know it’s real position due to transducers values loss and as seen even from the first measurements, the average accuracy positioning error for the uncalibrated robot are at the speed of 10% about 18.52 mm in the front cube and about 43.58 mm in the side cube. These huge errors show clearly that the calibration with the pendulum kit was mandatory to be performed in order to reset the encoders values and to be able to operate with the robot in good conditions.
2. As for the repeatability tests, the results show that it was a good idea to complete all the tests with the uncalibrated robot even if at a first glance the errors were huge. This is because the repeatability errors for the uncalibrated robot are as follows: 10% and 10 cycles = 0.025 mm, 10% and 20 cycles = 0.02 mm and at 10% and 30 cycles = 0.013 mm. The other tests at higher speeds also showed errors between 0.02 mm and 0.108 mm (maximum at 60% speed) indicating that even the resolver values were not correct, and the robot lost its real position, the repeatability wasn’t as much affected. This suggests that even in that condition it was hard to observe that the robot had problems if it would be programmed only by teaching targets using the teach-pendant because it would reach them fine. The problem could only be noticed if the robot had been programmed from the code (by ABB Robotstudio programming) by observing that the robot reaches far away from the programmed targets.
3. To improve the absolute accuracy of the robot the calibration procedure was performed by applying to an ABB pendulum kit system. The calibration procedure was also performed following up full experimental stages provided in the ABB pendulum kit operation manual and ABB IRB 140 robot calibration procedure manual.
4. The results obtained after the robot's calibration were calculated and averaged in the same manner as above. The values for the position accuracy tests are as follows: 10% front cube = 0.641 mm, 10% side cube = 0.475 mm; 20% front cube = 0.724 mm; 20% side cube = 0.488 mm; 40% front cube = 0.618 mm, 40% side cube = 0.508 mm; 60% front cube = 0.558 mm; 60% side cube = 0.504 mm. For the repeatability tests of the calibrated robot the averaged errors are: 10% and 10 cycles = 0.040 mm, 10% and 20 cycles = 0.044 mm, 10% and 30 cycles = 0.065 mm; at speed of 20% and 10 cycles = 0.060 mm, 20% and 20 cycles = 0.082 mm, 20% and 30 cycles = 0.072 mm; at speed of 40% and 10 cycles = 0.095 mm, 40% and 20 cycles = 0.147 mm, 40% and 30 cycles = 0.129 mm; at speed of 60% and 10 cycles = 0.143 mm, 60% and 20 cycles = 0.120 mm, 60% and 30 cycles = 0.130 mm.
All the accuracy measurements shown values between 0.4 and 0.72 values that are under maximum accuracy stated by the manufacturer of 0.8 mm.
5. In terms of repeatability the errors are above the stated one of 0.03 mm being effectively identified within 0.044 and 0.143 mm. From the results it can be observed that with the rise of speed the repeatability errors are also increase. With values of 0.044 mm at speed of 10% and 10 cycles up to 0.065 mm at 30 cycles it seems that the error has doubled at the speed of 40% with values of 0.095 mm for 10 cycles up to 0.129 mm for 30 cycles. At the speed of 60% the repeatability errors are reaching a maximum of 0.143 mm. In terms of precision accuracy, the results do not indicate any
influence between the speed and the accuracy errors. The results show only a better accuracy up to 20% measured in the side cube but due to the fact that the robot space was limited and in the side cube were measured only 27 points instead of 45 as in the front cube this can be put on the smaller number of points measured.

6. In terms of robot operation for real applicative works it may be concluded also, that:
- along performing different tasks usually considered as "pick and place" activities (that usually are not involving accurate / 3D complex path generation and may be easily accomplished by simply applying to the teach-in programming procedures), as is the case for palletizing, machine tending (loading / un-loading of CNC machine-tools, presses or injection moulding machines) and so on, the robot accuracy is less important than robot repeatability and even a low (rapid) calibration method performed by means of marks existing on the robot's joints may be enough precise to satisfying the specific requests of convenient operation modes for such robotic applications;
- beside of these, along performing tasks usually considered as mandatory involving "tool-path generation" (that usually involve accurate / 3D complex path generation by applying to off line programming software operating with virtual controller / importing into the robot controller a complex tool-path previously generated in some CAM software) as is the case for arc welding, plasma / laser water-jet processing as well as some complex robot machining tasks impossible to be programmed by simply teach-in programming procedures, or respectively involving complementary peripheral robotic systems as well as multiple robot cooperation (multi - move tasks) supplementary to the robot's repeatability, the robot absolute accuracy become also very important, for these cases being necessary to apply to a much more precise robot calibration procedure involving the pendulum kit;
- finally, in case of inappropriate operation maintenance of volatile memory (batteries overtime exchanging) or major service activities leading to encoders information loss the evaluation of robot absolute accuracy become mandatory and a full high precise calibration procedure need to be performed by using the pendulum kit or some equivalent (in performances) calibration system.

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