Recording procedure of thermal field distribution and temperature evolution on ABB IRB 140 industrial robot

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Abstract. The procedure and the results of recording the thermal field distribution and the evolution of the temperature of some heat sources (electric motors areas) are presented in this paper. Heat distribution and temperature evolution of heat sources are needed to develop a theoretical model by finite element analysis (FEA) of the robot with the purpose of identifying thermal induced displacements and effects of robot’s accuracy and repeatability. These data are required for the development of mathematical model able to compensate the errors generated by elastic thermal deformations. Thermal distribution recording and data processing was made with an infrared THERMACAM SC640 and THERMACAM RESEARCHER software and temperature evolution was recorded by motor mounted thermocouples connected with LABVIEW software via a data acquisition interface.

1. Introduction
As part of first authors PhD work on evaluating thermal behavior of industrial robots (IR) and influence of thermal errors on robot’s accuracy and repeatability, first steps on developing a mathematical model to compensate these errors were presented in [1], [2] and [3]. In this paper were presented and validated some simplified geometric models that will be used further for developing a more elaborate mathematical model for compensation of errors induced by thermal deformations of IR’s structural elements. To be able to complete the mathematical model with parameters for thermal errors compensation these factors must be quantified. Previously [4] the robot has been calibrated and evaluated with the help of a laser-tracker system so it’s state in terms of absolute accuracy and repeatability is known. The next step for advancing with the mathematical model is to identify the how the heat is distributed on the robot’s structural elements and how the heat generated by the motors is evolving during robot’s operation. The information and results from this experimental study will be further processed and used as input data into a FEA analysis (a future paper). After the FEA model will be complete and the analysis data will be processed, finally, only then the influence of the thermal deformation upon the robot’s accuracy and repeatability it will be quantified and expressed as parameters ready to be added to the compensating mathematical model. Further the equipment, followed procedures and results of this experimental study are presented.

2. Experimental set-up
The robot on which the measurements are made is an ABB IRB 140 model. The elements that are monitored for thermal evolution and considered as heat sources in this study are the motors. The robot has an asymmetrical structure and the motors distributed on the robot’s structure as follows: motors for axes 1 and 2 are placed outside, motor for axis 3 is placed inside the second link of the robot and motors for axes 4, 5 and 6 are centralized inside the back of the 3rd link. Directly on the motors were placed the temperature sensors (thermocouples). To have access to all the motors some of the robot’s elements had to be disassembled first. The thermocouples were attached on the motors and to ensure the contact thermic conductivity paste was put on everyone. Motors placement is depicted in figure 1a. Locations of thermocouples on the real robot can be observed in figure 1b.
After the thermocouples were placed, the covers were reassembled and then the wires were connected to the acquisition equipment. The acquisition equipment is collecting data from the thermocouples and send it via USB connection. On the PC a LABVIEW program processes these data and display them in real time on the graphic interface and stores them into a “log” file for later processing. A part of the equipment setup can be observed in following figures.

The LABVIEW software application consists in two parts. One block diagram which contains all the connections and instructions responsible for USB data interpretation and one user interface. The block diagram and the user interface are presented in figures 4 and 5.
The infrared camera is placed in the front of the robot and it is connected to a second PC with “Thermacam researcher” software installed for image processing. The laser-tracker is also part of the set up but laser-tracker results about robot’s repeatability during heating progress it’s an issue to be discussed in a future paper. The following figure represents the full experimental set-up used for this thermal observation study.

![Experimental set-up](image-url)
3. Measurement procedure

Multiple measurements were made during several days in approximately similar ambient conditions. The robot’s environment temperature was monitored with the help of a room thermometer. The robot was programmed to execute some movement cycles with the possibility of speed adjustment at 20, 40 and 60% percent of the robot’s full speed. Since the laser-tracker was also measuring robot’s position and the reflective sphere was mounted on the robot’s flange, no supplementary load was attached to the robot. This is the same reason why the upper speed limit was set up to 60% as an extra measure that the magnetic reflector doesn’t move or detach. Heat distribution and thermic evolution were recorded simultaneously from the cold start of the robot by the infrared camera and respectively the thermocouples and corresponding equipment. Between the measurements, the robot was always let to cool off an entire night. This procedure was established to follow three main objectives:

a) to observe the evolution of temperature in heat sources areas (electric motor zones), influence of working speed on temperature evolution and the thermal stabilization time of the robot for different working speeds.

b) to observe how the heat generated by the motors is distributed on the robot’s structural elements.

c) to observe how / if the robot’s repeatability is affected by the robot’s thermal evolution (this to be discussed in a following paper).

4. Experimental results

The LabVIEW application was set up to record the temperature at every 10 seconds while the infrared camera was set to continuously record at a framerate of 3.75 frames per second. The data from the LabVIEW application was processed and exported in excel format with timestamps to be better interpreted. Data from the infrared camera was processed directly on the camera’s corresponding software. Examples of obtained data formats are presented in figures 6 and 7.
4.1 Test 1 – speed 20%

The room thermometer showed a temperature value of the environment of 9 °C at the start of the test and a temperature of 9.8 °C at the end of the measurements. The plot function of the camera software registered 3 areas marked on the robot structure (at surface) and shows start values about 7 °C. Also, the data measured by the sensors attached on the robot motors show start values also between 6 and 7 °C. Temperatures monitored for by the sensors attached on the motors surface for the 20% moving cycle can be observed in following figure.

![Temperature evolution at 20% speed](image)

**Figure 9.** Temperatures at motors surface during 20% speed moving cycle

The recordings were made during a time of about 3 hours and 20 minutes of continuous moving cycle. On the last 20 minutes, the records show maximum increases of temperatures between 0.2 and 0.4 °C suggesting that the robot entered on the thermal stabilization line. During this full cycle the maximum temperatures detected by the sensors attached to the motors are as show in table 1.

| Axis 1   | Axis 2   | Axis 3   | Axis 4   | Axis 5   | Axis 6   |
|----------|----------|----------|----------|----------|----------|
| Max temp [°C] | 16.171523 | 17.100602 | 17.961056 | 20.587628 | 25.641935 | 28.9933  |

**Table 1.** Motor maximum temperatures reached at 20% speed cycle

As it can be observed for axes 1 and 2, both placed at the outside of the robot are following a similar heating path almost on the entire cycle. Also, the robot environment does not have a heat control system and the fact that the room (air) temperature was low this also helped these two motors to dissipate heat more easily. Very close to them is the motor for axis 3 which is enclosed and isolated single in the robot’s structure as shown in figure 1. These motors (also the transmissions) are considerably bigger and powerful than the last three motors. The last three motors are enclosed in the back of the robot’s upper arm which may be a fact that facilitates the heat to build up. The infrared camera recorded during this time the heat distribution on the robot’s structural elements. The infrared images of the robot and the heat distribution for the first 20 minutes, after an hour and for the last 10 minutes are presented in figures 10 (a, b, c) and 11 (a, b, c).
Figure 10. Infrared images of the robot during operation at 20% speed

Each histogram shows the temperature fluctuations in the areas marked with 1, 2 and 3 on the infrared images (previous figure 10). These marked areas spaces on the infrared images where the robot zones of interest are always passing during operation. Having the above figures presented, maximum temperature values measured at the surface of the robot are as presented in table 2.

| Area 1 | Area 2 | Area 3 | Middle area (motor 3 location) based on scale bar |
|--------|--------|--------|-----------------------------------------------|
| 18.8   | 18.9   | 19     | 16.5                                          |

Table 2. Maximum temperatures at surface at 20% speed cycle [°C]
4.2 Test 2 – speed 40 %
At the beginning of this test the room thermometer indicated an environment temperature of 8.8 °C at the start of the test and a temperature of 9.2 °C at the end of the measurements. The histogram of the infrared camera registered 3 areas marked on the robot structure (at surface) and starts at values about 7 °C. Also, the data measured by the sensors attached on the robot motors show start values also between 6 and 8 °C. Temperatures monitored for by the sensors attached on the motors surface for the 40% moving cycle can be observed in following figure.

These records were made also during a period of about 3 hours of continuous moving cycle. Like the previous tests, in the last 20 minutes of the measurements, the records show maximum increases of temperatures between 0.2 and 0.5 °C suggesting that the robot entered on the thermal stabilization line. During this full cycle the maximum temperatures detected by the sensors attached to the motors are as show in table 3.

| Axis 1   | Axis 2   | Axis 3   | Axis 4   | Axis 5   | Axis 6   |
|----------|----------|----------|----------|----------|----------|
| Max temp [°C] | 17.7911  | 18.8858  | 18.0573  | 21.3894  | 26.6810  | 30.4493  |

Again, the temperature curves seem to follow the same trends as previous. First three motors being very appropriate as values during the entire working cycle. To the last three motors seems to correspond again very distinct heating curves with the motor 6 reaching again the highest temperature followed by motor 5 and then 4. As values, in comparison with the previous test (done at 20% speed) now the heating curves seems to bee a little more abrupt. After 30 minutes now, the values for all sensors seems to be with approximately 2 °C higher. After 60 minutes, the values are still about 2 °C higher than the previous. This time the robot seems to enter on the stabilization line with values a little bit higher than previous, between 0.8 and 1.8 °C.

The infrared images of the robot and the heat distribution at the beginning and at the end of the measurements are presented in figures 13 (a, b) and 14 (a, b).
Figure 13. Infrared images of the robot during operation at 40% speed

Figure 14. Histogram of temperature evolution of the robot during operation at 40% speed

Maximum temperatures values reached during 40% speed cycle are presented in table 4.

| Area 1 | Area 2 | Area 3 | Middle area (motor 3 location) based on scale bar |
|--------|--------|--------|--------------------------------------------------|
| 20.0   | 21.1   | 20.2   | 17.5                                             |

As can be seen (even from the previous tests) some surfaces of motors 1 and 2 show maximum temperature values slightly bigger than sensor detected ones. From the infrared images it can be observed that the sensors have not been attached on the motors surfaces that become the hottest during robot work. Maximum final values recorded at 40% speed are between 1 and 2.2 °C bigger than the
maximum values recorded at 20 % speed. This indicates that the motor heating is slightly by the robot’s moving speed.

4.3 Test 3 – speed 60 %
At the beginning of this third test the room thermometer indicated an environment temperature of 10.9 °C at the start of the test and a temperature of 9.2 °C at the end of the measurements. The histogram of the infrared camera registered 3 areas marked on the robot structure (at surface) and starts at values about 12 °C. Also, the data measured by the sensors attached on the robot motors show start values also between 7 and 8 °C. Temperatures monitored for by the sensors attached on the motors surface for the 40% moving cycle can be observed in following figure.

These records were made also during a period of about 3 hours of continuous moving cycle. Like the previous tests, in the last 20 minutes of the measurements, the records show maximum increases of temperatures between 0.1 and 0.4 °C suggesting that the robot entered on the thermal stabilization line. During this full cycle the maximum temperatures detected by the sensors attached to the motors are as show in table 5.

| Axis 1 | Axis 2 | Axis 3 | Axis 4 | Axis 5 | Axis 6 |
|-------|-------|-------|-------|-------|-------|
| Max temp [°C] | 18.837 | 21.596 | 18.849 | 21.665 | 27.537 | 30.705 |

This time the temperature curves are following almost same paths with the observation that this time motor for axis 3 follow a little higher trend than motors 1 and 2 and it is this time closer to the temperatures of the fourth motor. This time the maximum values detected by the thermocouples were again a little bigger than the 40% speed previous test, increase varying between 0.2 and 2.7 °C. This time also this slightly increase of temperature is indicating again a slightly correlation with the increase of working speed.
The infrared images of the robot and the heat distribution at the beginning and at the end of the measurements are presented in figures 16 (a, b) and 17 (a, b).

![Infrared images of the robot during operation at 60% speed](image1)

**Figure 16.** Infrared images of the robot during operation at 60% speed

![Histogram of temperature evolution of the robot during operation at 46% speed](image2)

**Figure 17.** Histogram of temperature evolution of the robot during operation at 46% speed

Maximum temperatures values reached during 60% speed cycle are presented in table 6.

| Area 1 | Area 2 | Area 3 | Middle area (motor 3 location) based on scale bar |
|-------|-------|-------|-----------------------------------------------|
| 21    | 22.6  | 21.4  | 19.2                                          |

Maximum final values recorded at 60% speed are between 1 and 1.7 °C bigger than the maximum values recorded at 40 % speed and between 2.2 and 3.7 °C bigger than the 20% speed measured values. Evolution of maximum recorded values at robot surfaces in the mentioned areas is presented in table 7 and figure 18. Evolution of maximum recorded values recorded by the thermocouple sensors are presented in table 8 and figure 19.
Table 7. Evolution of maximum recorded values at robot surfaces [°C]

| AREA 1 | AREA 2 | AREA 3 | Middle area |
|--------|--------|--------|-------------|
| Test 1 (20%) | 18.8   | 18.9   | 19          | 16.5 |
| Test 2 (40%)  | 20    | 21.1   | 20.2        | 17.5 |
| Test 3 (60%)  | 21    | 22.6   | 21.4        | 19.2 |

Table 8. Evolution of maximum recorded values by the sensors [°C]

| Axis 1 | Axis 2 | Axis 3 | Axis 4 | Axis 5 | Axis 6 |
|--------|--------|--------|--------|--------|--------|
| Test 1 (20%) | 16.17152 | 17.1006 | 17.96106 | 20.587628 | 25.64194 | 28.9933 |
| Test 2 (40%)  | 17.7911 | 18.8858 | 18.0573 | 21.3894 | 26.681 | 30.4493 |
| Test 3 (60%)  | 18.837 | 21.596 | 18.849 | 21.665 | 27.537 | 30.705 |

Figure 18.

Figure 19.

Increase of temperatures (at surfaces fig. 18 and detected by the thermocouples fig. 19) are presented in percentages in tables 9 and 10.

Table 9. Surfaces temperature variation in percentages

| [increase %] | AREA 1 | AREA 2 | AREA 3 | Middle area |
|--------------|--------|--------|--------|-------------|
| t2 / t1      | 6.38   | 11.64  | 6.32   | 6.06 |
| t3 / t1      | 11.70  | 19.58  | 12.63  | 16.36 |

Table 10. Motors temperature variation in percentages

| [increase %] | Axis 1 | Axis 2 | Axis 3 | Axis 4 | Axis 5 | Axis 6 |
|--------------|--------|--------|--------|--------|--------|--------|
| t2 / t1      | 10.01  | 10.44  | 0.54   | 3.89   | 4.05   | 5.02   |
| t3 / t1      | 16.48  | 26.29  | 4.94   | 5.23   | 7.39   | 5.90   |
5. Conclusions
All proposed objectives have been accomplished. The works presented in this paper conclude related to:

a) Identifying the thermal distribution of temperature in overall industrial robot general assembly by focusing especially on getting information about heat sources areas (electric motor zones). Theses information will be necessaries for checking in thermal modeling by FEM the industrial robot behavior based on actual experimental evaluation.

b) The thermal distribution evaluation by thermo-graphic means allow identifying main heat sources and heating distribution previously to modeling so will improve the accuracy of FEM which will be developed further.

c) The influence of IR’s working speed on temperature evolution and the thermal stabilization time of the robot for different working speeds have been investigated too.

d) In order to have real information about motors temperature and as well to calibrate the FEM model information from thermocouples have acquired. This information will allow a precise defining of the heat sources that will be included in the FEM modeling and to evaluate specific values for the heat generated by the motors distribution on the robot’s structural elements.

e) Present results got from experimental results will also be useful in evaluating the robot’s thermal behavior in terms of thermal displacement of IR’s structural elements by means of FEM models and further by appealing to analytical extended geometric model of the robot to evaluate the influence of this thermal displacements on IR’s accuracy and repeatability (these aspects being subjects to be discussed in some following papers).

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