Proceedings in Manufacturing Systems, Volume 16, Issue 2, 2021, 69-74 ISSN 2067-9238

WARM-UP TEMPERATURE PREDICTIONS OF IRB 140 ROBOT WITH REGRESSION ANALYSIS

Cozmin CRISTOIU[1,*], **Mario IVAN**[2]

[1]Lecturer, PhD., Eng., Robots and Manufacturing Systems Department, University "Politehnica" of Bucharest, Romania
[2] Lecturer, PhD., Eng., Robots and Manufacturing Systems Department, University "Politehnica" of Bucharest, Romania

Abstract: *The cold start of a robot implies a heating period in which the positioning error of the robot is greatly influenced by the thermal variations of the structural elements that suffer thermal deformations and expansions. Due to this continuous variation of the positioning deviation caused by thermal deformations, the compensation of these errors is very difficult to do because the parameters used as compensation factors should vary continuously considering several factors such as robot temperature, operating time from start or working speed of the robot. Unfortunately, the thermal behavior of robots differs from model to model, differs depending on environmental conditions and working conditions, and there can be no common general mathematical model to solve this problem. Thus, based on real measurements, a heating pattern of a robot can be identified and may be used for correction of thermal deformation errors. As a first step in finding a compensation method of these errors, the anticipation of heating curves of an articulated arm robot is presented in this paper. Regression analysis is applied on experimental temperature recordings and the equation parameters are identified for function approximation of the heating curves.*

Key words: *industrial robot, heating, approximation, regression analysis, error.*

1. INTRODUCTION

Accuracy of industrial robots is influenced by temperature and deformations caused by heating especially for articulated arm types where the serial configuration of the mechanical structure causes the errors to cumulate from the base to the end point of the robot. There may be multiple heat sources internal to the robot or from the environment as analyzed in [1, 2] but regardless of the heat source the most important condition is that it is somewhat constant. As already identified in [3], the heat generated by the internal components of IRB 140 robot, although it does not follow a linear curve, is still relatively constant, constantly increasing until a level of thermal stability is reached (after about three hours of continuous operation). The problem that remains is regarding the environment temperature of the robot. If this fluctuates to much or is completely random, it will induce a random thermal behavior of the robot structure that will be hard or impossible to predict. From this point of view, the first condition that we must meet is to ensure that the robot operates in an environment thermally stable so that the approximation of the heating behavior to be possible. This fact is in most of the cases true because industrial robots are usually used in factories/facilities with climate-controlled environment. Derived from this first condition comes a second that requires that experimental measurements be made in ambient temperature conditions very similar to those in which the robot will operate. If these two conditions are met, there are two stages of the robot thermal behavior and thermal induced errors evolution:

- period of thermal transition (warm-up cycle);
- period after warm-up after robot reaches thermal stabilization.

Now, having in mind the final goal of developing a software compensation method for thermal induced errors, for each of these two stages, the following main objectives and necessary research activities must be done:

O1) Identifying a software compensation method for thermal induced error of the robot during warm-up cycle (the error varies continuously).

a1) Identification of a method for integrating a thermally deformed virtual model of IR studied, within an offline programming and simulation software application, for the evaluation by simulation of positioning errors in the entire RI workspace or identification of a method of correction of programmed paths/points by applying continuous coordinates corrections based on estimated thermal deformations and errors, or by altering the programmed targets online or offline. For the transient thermal state of the robot during the worm-up.

a2) Measurements of robot temperature evolution during warm-up cycle.

a3) Quantitative evaluation/determination of positioning errors during the warm-up cycle.

---

[*] Corresponding author: Splaiul Independenței 313, district 6, 060042, Bucharest, Romania,
Tel.: 0040 21 402 9174,
Fax: 0040 21 402 9724,
E-mail addresses: *cozmin.cristoiu@gmail.com* (Cristoiu C.)

a4) Find correlation between temperature induced errors and actual temperature.

a5) Temperature prediction and estimation as a function of time.

O2) Identifying a software compensation method for thermal induced error after the robot reaches the thermal Stabilization (the error remains constant).

b1) Identification of a method for integrating a thermally deformed virtual model of industrial robot (IR) studied, within an offline programming and simulation software application, for the evaluation by simulation of positioning errors in the entire IRI workspace or identification of a method of correction of programmed paths/points by applying coordinates corrections based on determined measured error, or by altering the programmed targets online or offline. For the steady thermal state of the robot (after thermal stabilization is reached).

b2) Measurements of robot temperature after warm-up.

b3) Quantitative evaluation/determination of the positioning error after warm-up.

To achieve final objectives O2 and O1, their subsequent research activities must be done in reverse order as they were mentioned. Regarding the robot model ABB IRB 140, steps b2 and b3 were studied previously in [3, 4, 5]. Among the major objectives and research activities previously described, this paper aims to check step a5 by identifying numerical values of an equation parameters that can predict/approximate heating curves of the robot (predict temperature as a function of time).

2. MATHEMATICAL APPROACH

Thermal behavior of the robot can be monitored with temperature sensors or with an infrared video camera. The best way to record temperatures of internal heat sources is by placing the temperature sensors directly or as close as possible to the elements that are heating up in the robot structure [6]. Still, local temperature values are not enough, because as shown in [7] very important is the heat distribution which is not the same in the robot structure. Due to the serial structure and configuration of the robot, thermal drift can't be considered as simple linear displacements of the elements because they also twist in ways that affect the orientation of the robot's endpoint. So, for determination of both linear and angular displacements, a finite element model (FEM) and analysis is needed. For this analysis, beside the location and values of the heat sources, the real heat map is also needed for calibration of the FEM model. The start of the journey of thermal compensation of industrial robots is represented by the experimental determination of temperature values and is further presented.

During experimental investigation of the thermal field distribution and temperature evolution of the robot, temperature readings were recorded every 5 seconds for each of the robot axes by placing temperature sensors on the motors. The positions of the motors in the robot structure are presented in Fig. 1.

The locations of the temperature sensors can be observed in Fig 2.

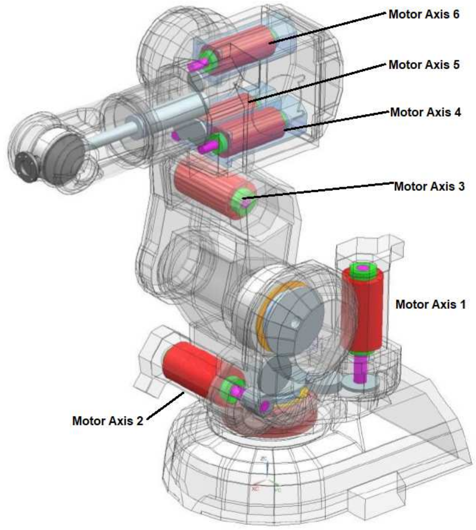

Fig. 1. Motors placement of IRB 140 robot model [4].

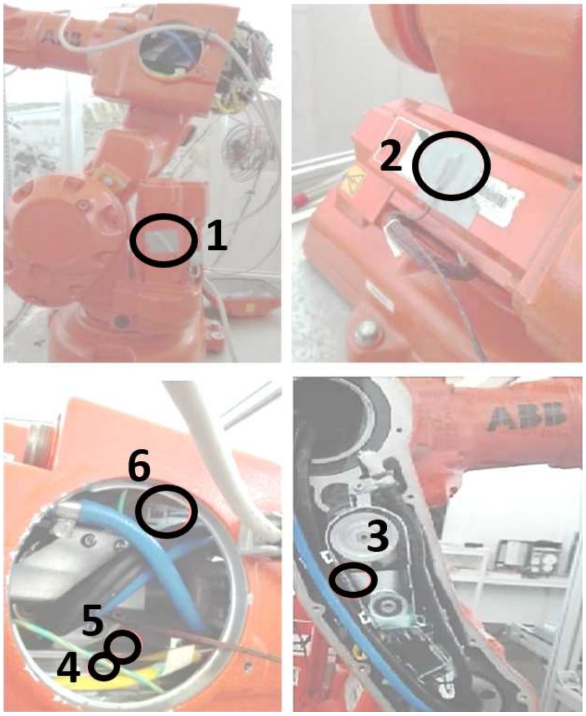

Fig. 2. Temperature sensors placement on and in the robot [4].

During the experiments, it was identified that in the given environmental conditions (approximately 7 °C at the start of the robot) the warm-up time is about 3 hours.

There have been many measurements for different working speeds of the robot but the values for this paper were only the data recorded for the 60% of the maximum speed. During that cycle, there were 2017 records for each of the robot segments. The temperature recordings were saved in *csv* format and then processed in an excel spreadsheet.

By plotting the data of the recorded values, the heating curves were obtained. The curves are presented in Fig. 3.

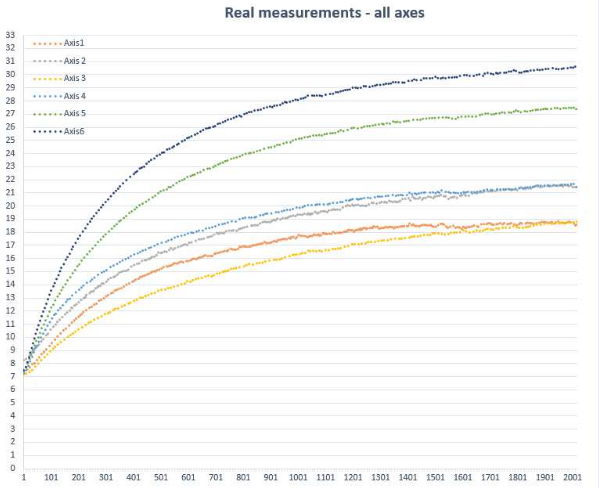

Fig. 3. Heating curves of robot axis during warm-up.

By looking at the curves we can observe that the temperature of each axis is gradually increasing with a steeper slope of the axis 4, 5 and 6 (there motors are enclosed in the upper arm of the robot). Regardless that the curves are not close to linear, the first method tried to fit the curves was linear regression, just as a starting point. For the linear regression, the equation form is the following:

$$\hat{y} = ax + b, \tag{1}$$

where coefficients *a* and *b* are:

$$a = \frac{\sum x_i \sum y_i - n \sum x_i y_i}{(\sum x_i)^2 - n\sum x_i^2}, \tag{2}$$

$$b = \frac{\sum x_i \sum x_i y_i - \sum x_i^2 \sum y_i}{(\sum x_i)^2 - n\sum x_i^2}. \tag{3}$$

The linear correlation coefficient *r* is:

$$r_{xy} = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{(n\sum x_i{}^2 - (\sum x_i)^2)(n\sum y_i{}^2 - (\sum y_i)^2)}}. \tag{4}$$

The coefficient of determination R^2 is:

$$R^2 = r_{xy}^2, \tag{5}$$

and the error of regression can be calculated by:

$$\bar{A} = \frac{1}{n}\sum\left|\frac{y_i - \hat{y}_i}{y_i}\right| \cdot 100\% \tag{6}$$

The linear regression was applied only for one axis recordings (for axis 1). The equation calculated was:

$$y = 0.0522x + 11.9655. \tag{7}$$

The linear correlation coefficient was r_{xy} = 0.8734, the coefficient of determination R^2 = 0.7628 and the average relative error *A* = 8.4031%. Because the temperature values are relatively slowly growing and there are no sudden big abrupt changes, the coefficients of correlation and determinations are quite high although due to the big number of recordings and the slope of the heating graph a straight graph (line) as approximated by the calculated equation cannot fit to the real curve and can only intersect and be relatively close enough to real values only in two points as shown in Fig. 3.

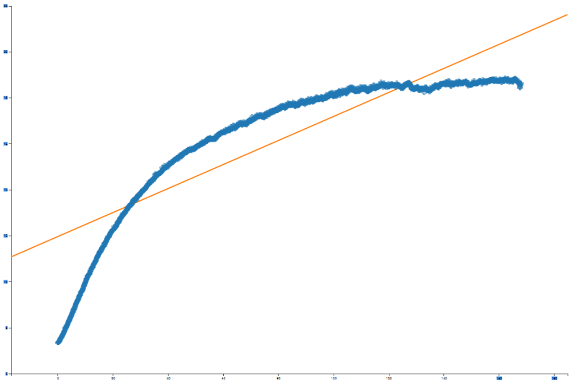

Fig. 3. Linear regression approximation over real heating curve of 1st robot axis.

The second attempt was with quadratic regression where the general equation is:

$$\hat{y} = ax^2 + bx + c, \tag{8}$$

and the system of equations with the unknowns a, b and c is:

$$\begin{cases} a\sum x_i^2 + b\sum x_i + nc = \sum y_i \\ a\sum x_i^3 + b\sum x_i^2 + c\sum x_i = \sum x_i y_i \\ a\sum x_i^4 + b\sum x_i^3 + c\sum x_i^2 = \sum x_i^2 y_i \end{cases}. \tag{9}$$

The correlation coefficient *R* is:

$$R = \sqrt{1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2}}, \tag{10}$$

where:

$$\bar{y} = \frac{1}{n}\sum y_i. \tag{11}$$

The coefficient of determination is $R^{2,}$ and the standard error is calculated the same as for linear regression. The same real temperature recordings (from axis 1) were used as input for the quadratic regression and the calculated equation is:

$$y = -0.0006x^2 + 0.1570x + 9.0328. \tag{12}$$

In this case the correlation coefficient was *R* = 0.9838, the coefficient of determination R^2 = 0.9679 and the average relative error *A* = 3.0125%. The graph of the approximation equation is plotted over the real measurements curve as shown in Fig. 4.

By analyzing the graph, it can be see that the approximation function tends to fit the real heating curve (unlike the linear regression graph). It is clearly that by rising the polynomial order of the function the similarity between the approximation function and the real curve will be closer.

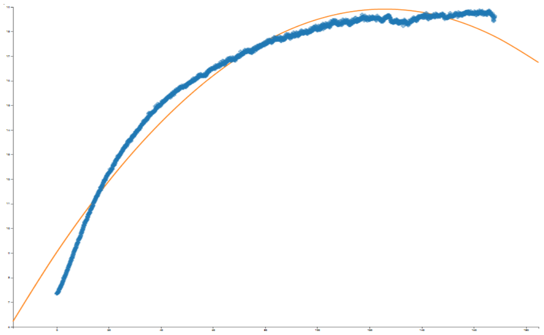

Fig. 4. Quadratic regression approximation over real heating curve of 1st robot axis.

The third try of computing the approximation function was made with cubic regression where the general equation is:

$$\hat{y} = ax^3 + bx^2 + cx + d, \tag{13}$$

and the system of equations with the unknowns a, b and c is:

$$\begin{cases} a\sum x_i^3 + b\sum x_i^2 + c\sum x_i + nd = \sum y_i \\ a\sum x_i^4 + b\sum x_i^3 + c\sum x_i^2 + d\sum x_i = \sum x_i y_i \\ a\sum x_i^5 + b\sum x_i^4 + c\sum x_i^3 + d\sum x_i^2 = \sum x_i^2 y_i \\ a\sum x_i^6 + b\sum x_i^5 + c\sum x_i^4 + d\sum x_i^3 = \sum x_i^3 y_i \end{cases}. \tag{14}$$

The correlation coefficient, coefficient of determination and standard error of the regressions are the same as in case of quadratic regression. The calculated equation is:

$$y = 0.000005x^3 - 0.001969x^2 + 0.247369x + 7.769163. \tag{15}$$

In this case the correlation coefficient was R = 0.9975, the coefficient of determination R^2= 0.99520 and the average relative error A = 1.1737%. The graph of the approximation equation is plotted over the real measurements curve as shown in Fig. 5.

The approximation function is in this case very close to the real heating curve. A very important aspect is that the number of decimals needed to calculate the parameters of the function increases. As can be observed, for parameter a of the cubic regression at least 6 decimals are needed. In the hope of reaching a better mean error, higher order polynomial regression curve fitting methods were tried but it seems that over the 4th order, the error could not be improved under 0.38% no matter the order, but the number of decimals needed to display the coefficients went over 9. So unable to foresee the final compensation method or the computing limitation of the software/hardware equipment that will be used to develop a compensation solution for the thermal induced errors of the robot accuracy, the cubic regression was chosen to further compute the curve fitting equations for the other 5 axis of the robot structure. Complete results are presented in the following chapter.

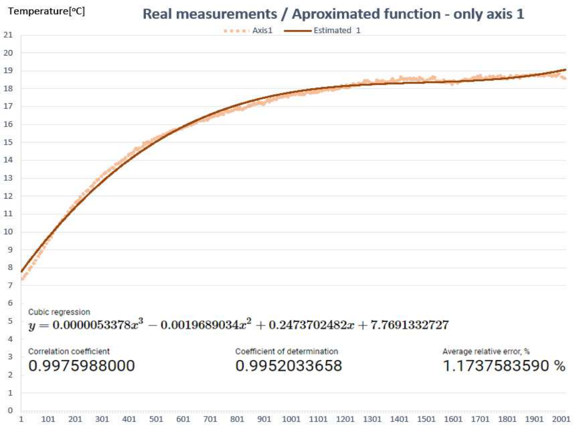

Fig. 5. Cubic regression approximation results over real heating curve of 1st robot axis.

3. RESULTS

The cubic regression was applied to compute all curve fitting equations for all 6 of the robot axes. The equations, parameters values, coefficients and error are presented further, individually for each for each axis (compared to real measured values/heating curves). Heating anticipation of second, third and fourth segments of the robot arm are presented in Figs. 6, 7 and 8.

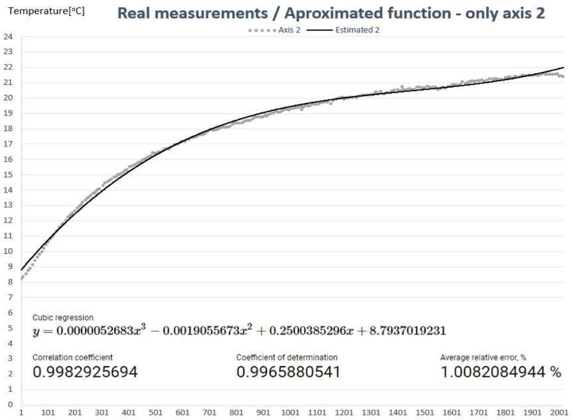

Fig. 6. Cubic regression approximation results over real heating curve of 2nd robot axis.

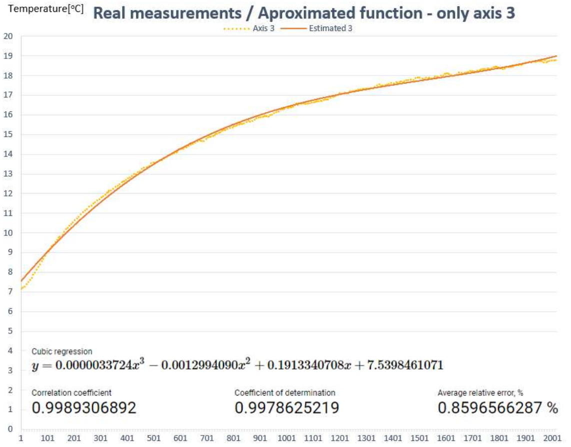

Fig. 7. Cubic regression approximation results over real heating curve of 3rd robot axis.

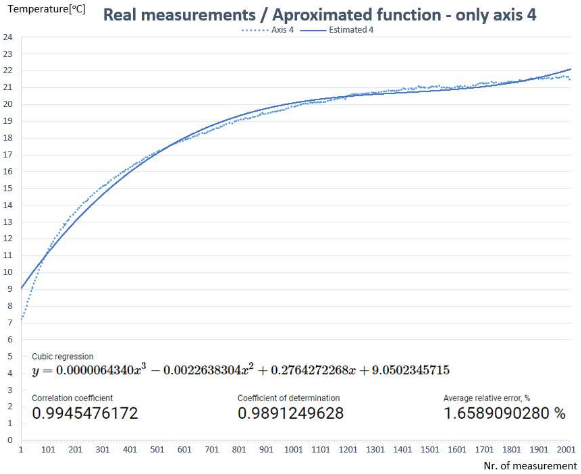

Fig. 8. Cubic regression approximation results over real heating curve of 4th robot axis.

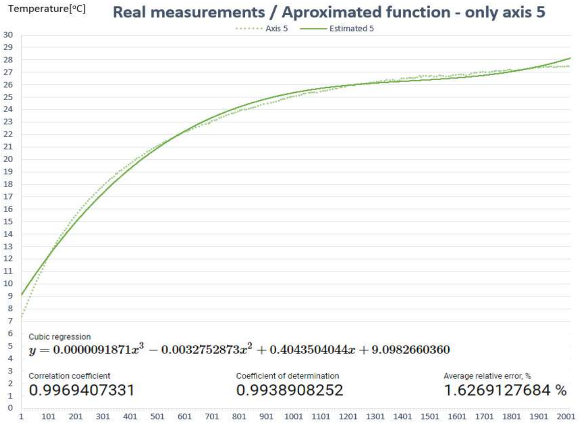

Fig. 9. Cubic regression approximation results over real heating curve of 5th robot axis.

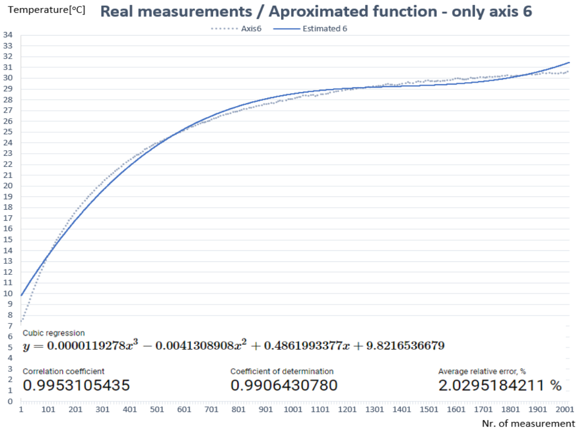

Fig. 10. Cubic regression approximation results over real heating curve of 6th robot axis.

At this moment, it can be observed an increase of the relative error of approximation caused by a steeper slope. The rise in temperature of the motors is a little higher for axis 4, 5 and 6 because they are encapsulated inside the upper arm of the robot making the heat to accumulate. Heating anticipation of the last two segments of the robot arm be observed in Figs. 9 and 10.

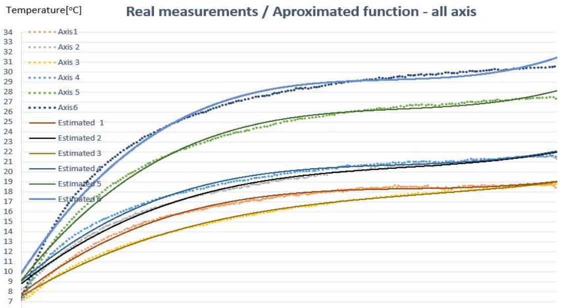

Fig. 11. Cubic regression approximation results for all 6 segments of the robot.

All 6 approximation functions and real heating curves of the robot are presented in Fig. 11.

The maximum average relative error is about 2.03% for the 6th axis of the robot which has the steepest slope of them all and the one for which the maximum temperature reached is the highest (about 31 °C). Even that the temperatures are not high, in the given environmental conditions of the robot working space at the time of experiments (about 7 °C) in [5] it was shown that even for these small temperature values the thermal deformation of the robot induces a drift of the endpoint (characteristic point) of about 0.097 mm that represents about 62% of the repeatability error and 12% of the precision error of this robot model meaning that thermal drift is inducing significant errors to even for relatively low temperatures of the robot or working environment.

7. CONCLUSIONS

Recalling the final objectives specified in the first chapter for developing a compensation solution for the errors caused by the thermal deformations of the robot, both for the warm-up period of the robot as well as for the steady thermal state, the results presented in this paper (as a result of research performed for postdoctoral project of the first author) solve the a5 sub-step of prediction and estimation of the temperature of the robot segments as a function of time (during warm-up). In the calculated equations all the parameters are known, and the temperature can be successfully predicted by replacing x with the time elapsed from the start of the robot. In future research, one expects the finding of the correlation between individual temperatures of each robot segments and thermal deformations measured at the end flange of the robot. If so, a compensation solution may be developed in order to increase the precision of the robot during the warm-up period and after the thermal stabilization. Two very important aspects must be considered:

a) Every robot model has a unique thermal behavior and for each robot model, the experimental procedures of temperature recordings and thermal drift must be performed.
b) The measurements and then the computing of the heating curves equations must be performed in a thermal stable environment like that in which the robot is planned to operate.

The measurements on IRB 140 robot model were performed in a quite cold environment in which the robot works (about 7 °C at the cold start of the robot, the temperature of the room from the laboratory at that time) would not fit if the robot needs to be moved and operate, such as in a 40 °C environment. The working conditions of the robot are mandatory to be known.

The predictions of the robot temperatures axes, performed by regression analysis provided results with a mean error of about 2.03% that represents less than 1 ˚C error. It should not be forgotten that higher polynomial order equations can provide much accurate predictions but with the downside of the bigger number of decimals needed to be computed for equations parameters and possible bigger computing capabilities of software/hardware equipment that the thermal compensation calculations will be performed.

The work presented and the results are closely related to [3, 4, 5] (and still needs a lot of future work to achieve the final objectives) represents a general template of theoretical and experimental procedures that can be replicated for any articulated robot arm and for different temperature conditions of the working environment of the robot. Of course, after the development of the thermal compensation solution, there are things that can be added and improved. For example, in [8, 9] friction between some of the robot components was considered as heat source and the results showed significant temperatures (up to 60 °C) caused by friction. But returning to the actual stage, presented in this paper, the plan for the near future research is to use calculated equations in the following step of finding a correlation between the thermal drift of the characteristic point of the robot as a function of time in the warm-up period of the robot.

REFERENCES

[1] C. Mavroidis, S. Dubowsky, P. Drouet, J. Hintersteiner, J. Flanz, *A systematic error analysis of robotic manipulators: application to a high performance medical robot*, Proceedings of International Conference on Robotics and Automation, IEEE, vol. 2, 1997, pp. 980–985.

[2] C. Mehdi, K. Jean-Yves, B. Alex, *Thermal aspects on robot machining accuracy*, Proceedings of IDMME – Virtual Concept 2010, France 2010.

[3] A.F. Nicolescu, C. Cristoiu, C. Dumitrascu, R. Parpala, *Recording procedure of thermal field distribution and temperature evolution on ABB IRB 140 industrial robot*, IOP Conference Series: Materials Science and Engineering, IOP Publishing, vol. 444, no. 5, 2018, p. 052023.

[4] C. Cristoiu, M. Zapciu, A.F. Nicolescu, C. Pupaza, *Thermal deformation analysis of ABB IRB 140 Industrial Robot,* UPB Scientific Bulletin, Series D: Mechanical Engineering, vol. 82, iss. 2, 2020, pp. 61–72.

[5] C. Cristoiu, *Research on the influence of the thermal behaviour of industrial robots on their performance*, PhD. Thesis, University "Politehnica" of Bucharest, 2020.

[6] Theissen, N. A., Mohammed, A., & Archenti, A., *Articulated industrial robots: An approach to thermal compensation based on joint power consumption*, Laser Metrology and Machine Performance, vol. 13, 2019, pp. 81–90.

[7] Mohnke, C., Reinkober, S., & Uhlmann, E., *Constructive methods to reduce thermal influences onthe accuracy of industrial robots*, Procedia Manufacturing, vol. 33, 2019, pp. 19–26.

[8] Simoni, L., Beschi, M., Legnani, G., & Visioli, A., *Friction modeling with temperature effects for industrial robot manipulator,* 2015 IEEE/RSJ international conference on intelligent robots and systems (IROS), IEEE, 2015. pp. 3524-3529.

[9] Hao, L., Pagani, R., Beschi, M., & Legnani, G., *Dynamic and Friction Parameters of an Industrial Robot: Identification, Comparison and Repetitiveness Analysis*. Robotics, vol. 10.1, no. 49, 2021.