Determining the Influence of the External Factors on the Firmware Response Time

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Abstract**—**The work deals with the problem of changes in the response time of hardware components of a real-time embedded system over time and under the influence of the environment. Simple models for predicting the change of the response time under influence of the supply voltage, the ambient temperature and the operation time of an electronic unit being evaluated have been proposed. The models sustained approbation with experiments.

Keywords**—**firmware execution time, hardware components, real-time embedded systems

I. INTRODUCTION

In hard real-time systems, each time-critical activity should meet its deadline. However, any firmware execution time depends not only on the microcontroller itself but also on peripheral devices connected to it, moreover, the latter can be inclined to more or less uncertainty in their response, depending on their type, model, the time of being in use, and the conditions of use. It's commonly known that each electronic unit is getting slower with age. Thus, any firmware's execution time depends not only on the computational resources of the embedded system being inspected but also on peripheral devices each of which is able to perform a set of operations during some random time period residing, however, within a known interval. Moreover, the ambient temperature influences a device, thus the latter might work slower in hot areas than in cold or moderate ones.

In order to evaluate the firmware's execution time, they use the following metrics [1]: worst-case execution time (WCET), best-case execution time (BCET) and average-case execution time, (ACET). The latter resides within the interval [BCET;WCET] and depends on the distribution of the program execution time. Evaluation of the firmware's execution time is typically performed *before* a system gets being in use and its results are considered invariable. However, the firmware's response time might change over time and in the case when the system's environment changes. The firmware's response time is unlikely to get better, thus a system previously considered useable might become no longer applicable some time moment during its operation, and this fact should be taken into account.

A range of methods has been developed for estimation of firmware execution time. They all fall into two large groups: static methods and dynamic ones. These methods are based either on the measurement of the actual execution time of firmware in a real embedded system [2], [3] or on predicting the range in which the firmware execution time resides [4]. References [5] – [7] present a detailed overview of methods and software tools intended for analysis of the execution time of a firmware.

None of the existing methods takes into consideration the influence of changes in external or internal physical quantities (supply voltage, ambient temperature, aging of the hardware components comprising an embedded system under evaluation and the fact that hardware gets worn-out over time). The work is aimed at the development of a model for evaluation of firmware execution time, that takes into account changes in the response time of electronic units

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under influence of changes in the supply voltage, ambient temperature, and aging.

II. Problem Statement

The text of any firmware that is comprised of a set of instructions, might be represented by a control flow graph (Fig. 1).

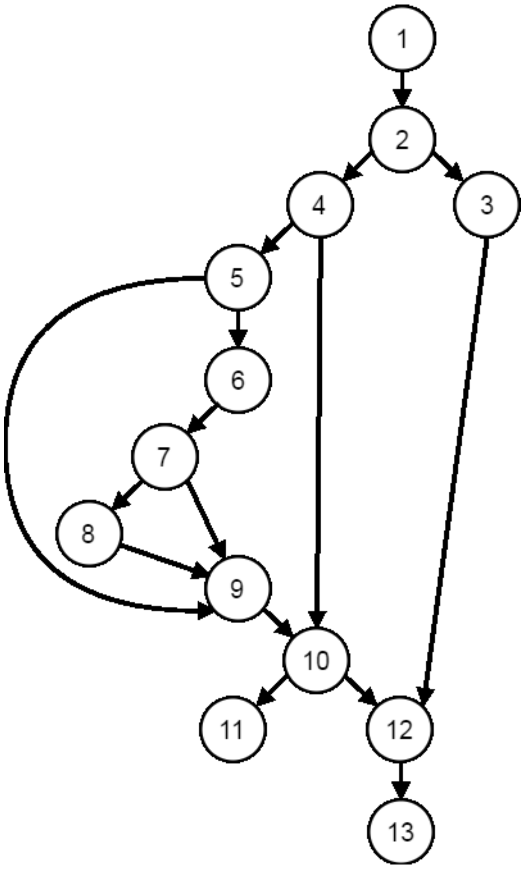

Fig. 1. An example of a control flow graph representing the code of a firmware function

The vertices of a control flow graph represent operators or functions that are characterized by some execution time. The edges show connections between different operators/functions. The whole execution time of a firmware code branch can be calculated by the following formula:

$$\tau_b = \sum_{i=0}^{n} \tau_i \quad (1)$$

where τ_i is the execution time of a certain vertex in the graph, n is the amount of vertices in a single path in the firmware being analyzed.

Making allowances for the fact that the execution time of any firmware depends not only on the computational resources of the underlying microprocessor but also on the response time of the peripheral devices included into the embedded system under investigation, one can describe the resulting execution time as follows:

$$\tau_b = \sum_{j=0}^{k} \tau_c + \sum_{i=0}^{n} \tau_v\,(param) \quad (2)$$

where τ_c is the execution time of a graph vertex that depends on the computation capabilities of the processor only; k is the amount of computational instructions with the constant execution time; $\tau_v(param)$ is the execution time of a graph vertex which depends on the response time of a peripheral device and may vary under influence of some internal or external physical quantity, n is the amount of computational operations with a variable execution time.

III. Experimental Data

In order to verify our assumption that the influence of the temperature, supply voltage, and age on the response time of an electronic unit is of any importance and is worth being taken into consideration, we started our investigation with a set of experiments with a thermocouple ADC ADS1118, and seeking for data on the dependence of the response time on aging of hardware components. The same data will be used for verification of analytical dependencies derived in this work.

Table I shows the dependency of the ADS1118's response time on the supply voltage. The nominal response time (in accordance with the official datasheet [8]) is 0.0078125 s. It can be easily seen that the discrepancy between the nominal response time and the actual one is up to 1.2% (the minus sign shows that the actual value is greater than the nominal one).

The data summarized in Table II do not represent the authors' experimental results; they were taken from [9]. One can notice that 3 months of operation reduce the response time by 10% whereas three years under operation worsen the response time by 18%.

Table III presents measurements of ADS1118's response time at different temperatures for two cases: 1) the supply voltage is fixed to 2V; 2) the supply voltage is fixed to 3.3 – 5V taken from [8]. The variance of the response time comes up to 2.4% in our specific case. The percentage itself might differ depending on electronic units being considered.

However, the main point remains the same – the unit's response time does depend both on temperature and supply voltage, as proved by experiments conducted by the authors and provided by the manufacturer.

When setting a measurement mode for ADC ADS1118, one of the parameters to be set is the number of conversions per second (and, consequently, the duration of any single conversion, or the response time).

TABLE I
THE DEPENDENCE OF THE ADS1118'S RESPONSE TIME ON THE SUPPLY VOLTAGE

Supply voltage, V	Response time, s	The difference between the nominal and actual values, %
2	0.00771875	-1.2
2.1	0.00771875	-1.2
2.2	0.007726563	-1.1
2.3	0.007734375	-1
2.4	0.007734375	-1
2.5	0.007742188	-0.9
2.6	0.007757813	-0.7
2.7	0.007773438	-0.5
2.8	0.007789063	-0.3
2.9	0.007804688	-0.1
3	0.0078125	0
3.1	0.007828125	0.2
3.2	0.007835938	0.3
3.3	0.00784375	0.4
3.4	0.007844531	0.41
3.5	0.007844531	0.41
3.6	0.007847656	0.45
4	0.007849219	0.47
4.5	0.00785	0.48
5	0.007851563	0.5

TABLE II
THE DEPENDENCE OF THE ADS1118'S RESPONSE TIME ON THE TIME OF BEING IN USE

Operation time, years	Response time, s	The difference between the nominal and actual values, %
0.25	0.00859375	10
0.6	0.00859375	10
1.7	0.00859375	10
1.9	0.008984375	15
2.2	0.008984375	15
3	0.00921875	18

TABLE III
THE DEPENDENCE OF THE ADS1118'S RESPONSE TIME ON THE AMBIENT TEMPERATURE AT THE SUPPLY VOLTAGE 2 V AND 3,3/5 V

Supply voltage, V	Response time, s (2 V)	The difference between the nominal and actual values, %	Response time, s (3,3/5 V)	The difference between the nominal and actual values, %
-60	0.007625	-2.4	0.00789063	1
-40	0.007648438	-2.1	0.00787500	0.7
-20	0.007671875	-1.8	0.00786719	0.6
0	0.007695313	-1.5	0.00785156	0.5
20	0.007710938	-1.3	0.00784375	0.4
40	0.007734375	-1	0.00784375	0.3
60	0.007746094	-0.85	0.00783594	0.3
80	0.007773438	-0.5	0.00783594	0.25
100	0.007789063	-0.3	0.00782813	0.25
120	0.007804688	-0.1	0.00782813	0.3
140	0.007820313	0.1	0.00783594	0.3

In order to have the possibility to predict the difference between the nominal response time and actual one for any value of the supply voltage, ambient temperature or time of being in use, one needs some analytical dependencies.

IV. DEVELOPING A MODEL

Having analyzed the above-presented data, one can assume that the sought-for analytic dependencies might be sufficiently well approximated by linear dependencies:

$$\tau = \alpha_n + \beta_n x, \tag{3}$$

where x – is the value of a physical quantity that influences the response time of an electronic unit (temperature, supply voltage, or aging period), α and β are the coefficients to be found.

In order to find the most suitable values for the coefficients, we have used LMS and derived the following formulas:

$$\alpha = \frac{\sum_{i=1}^{n} x_i \sum_{i=1}^{n} \tau_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} x_i \tau_i}{n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2}, \quad \beta = \frac{n\sum_{i=1}^{n} x_i \tau_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} \tau_i}{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}, \tag{4}$$

where τ_i – is the corresponding measured value of the response time (or taken from the technical reports).

Using formulas (4), we've calculated:

1) The coefficients that describe the influence of the supply voltage on the response time:

$$\alpha_1 = 7{,}622 \cdot 10^{-3};\ \beta_1 = 5{,}674 \cdot 10^{-5}; \tag{5}$$

2) The coefficients describing the influence of electronic units' aging on their response time:

$$\alpha_2 = 8{,}455 \cdot 10^{-3};\ \beta_2 = 2{,}317 \cdot 10^{-4}; \tag{6}$$

3) The coefficients describing the influence of the ambient temperature on the response time at the supply voltage 2V

$$\alpha_3 = 7{,}69 \cdot 10^{-3};\quad \beta_3 = 9{,}747 \cdot 10^{-7}; \tag{7}$$

4) The coefficients describing the influence of the ambient temperature on the response time at the supply voltage 3.3 – 5 V

$$\alpha_4 = 7.85994 \cdot 10^{-3};\ \beta_4 = -2.80527^{-7}; \tag{8}$$

Having substituted the calculated coefficients (5-8) in (3), we obtain the response time of a peripheral device influenced by each considered physical quantity. The result should be related to (2).

V. APPROBATION

In order to verify the obtained formulas, the following several steps were taken. First, we compared two plots for the dependence of τ on the supply voltage: one based on experimental results, another – on analytical dependencies (just for preliminary and very rough estimation).

Then, at the second step, we artificially reduced the number of experiments (n) from n = 20 to n = 15 and n = 10, i.e., we intentionally did not use part of experimental data for calculating the coefficients. Then we verified the differences between the values of τ calculated analytically, using the above-presented formulas, and the corresponding values of τ obtained experimentally. As expected, we noticed that the inaccuracy grows with reduction of data used for calculating of the coefficients. Finally, we performed several additional measurements (the results were not included in the calculation of the coefficients) to check how they fit the analytical curve. This approach is represented in Fig. 2 – Fig. 5. The same procedure was repeated for two remaining dependencies. The greatest calculation error for the dependency on the supply voltage is $5.4e^{-5}$, on the time of being in use – $2.56e^{-4}$, on the ambient temperature at the supply voltage 2V – $6.57e^{-6}$, on the ambient temperature at the supply voltage 3.3 – 5V – $1.52e^{-5}$, and this fact proves the applicability of the proposed model.

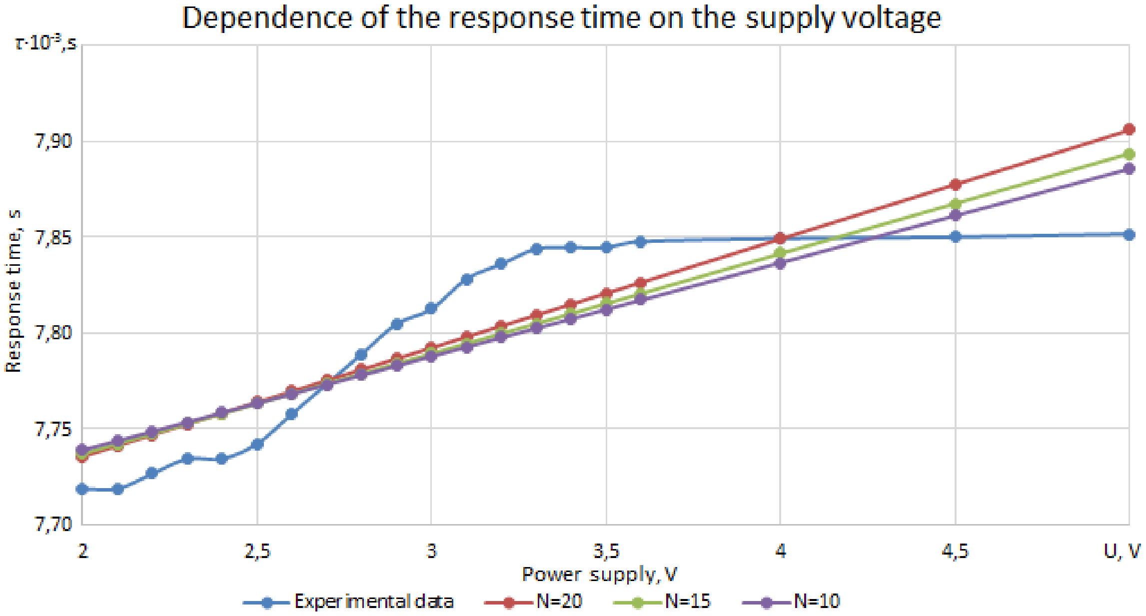

Fig. 2. The experimental and calculated dependencies of the response time on the supply voltage

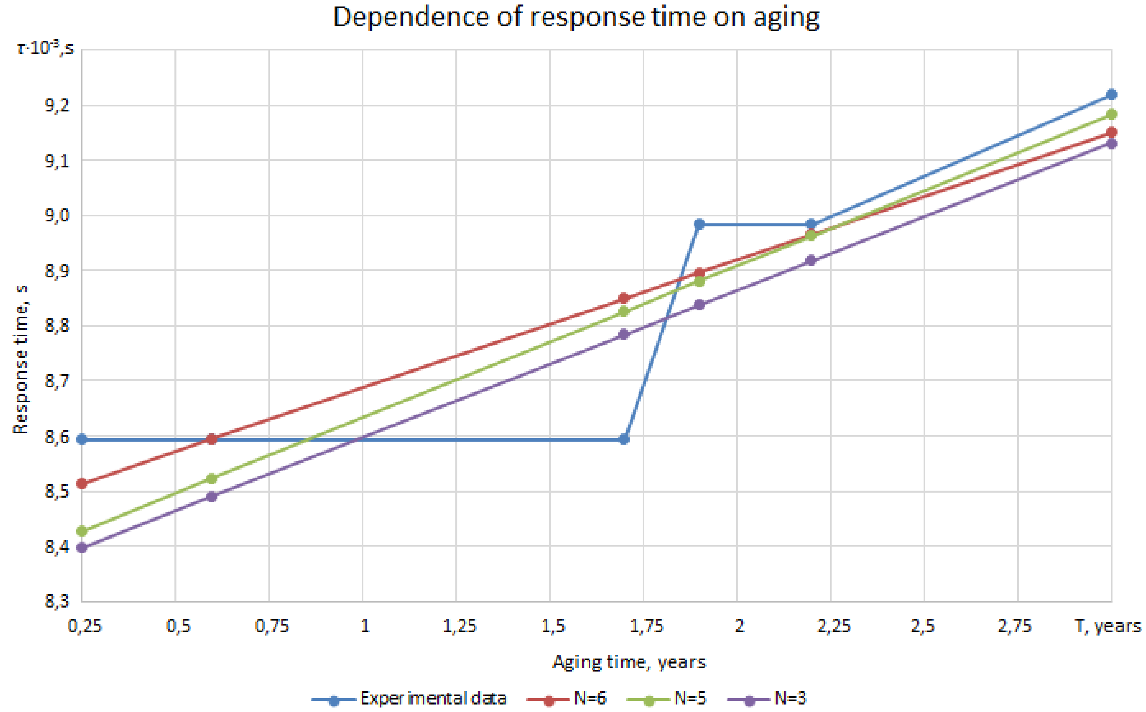

Fig. 3. The experimental and calculated dependencies of the response time on the time of being in use

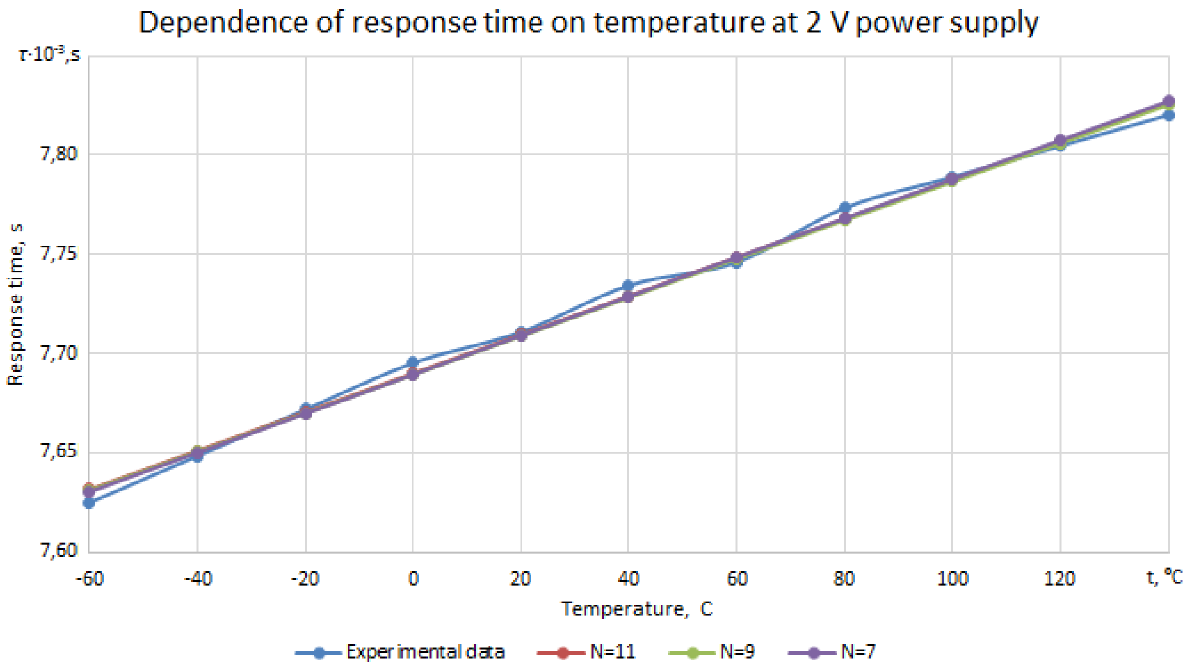

Fig. 4. The experimental and calculated dependencies of the response time on the temperature at the supply voltage 2V

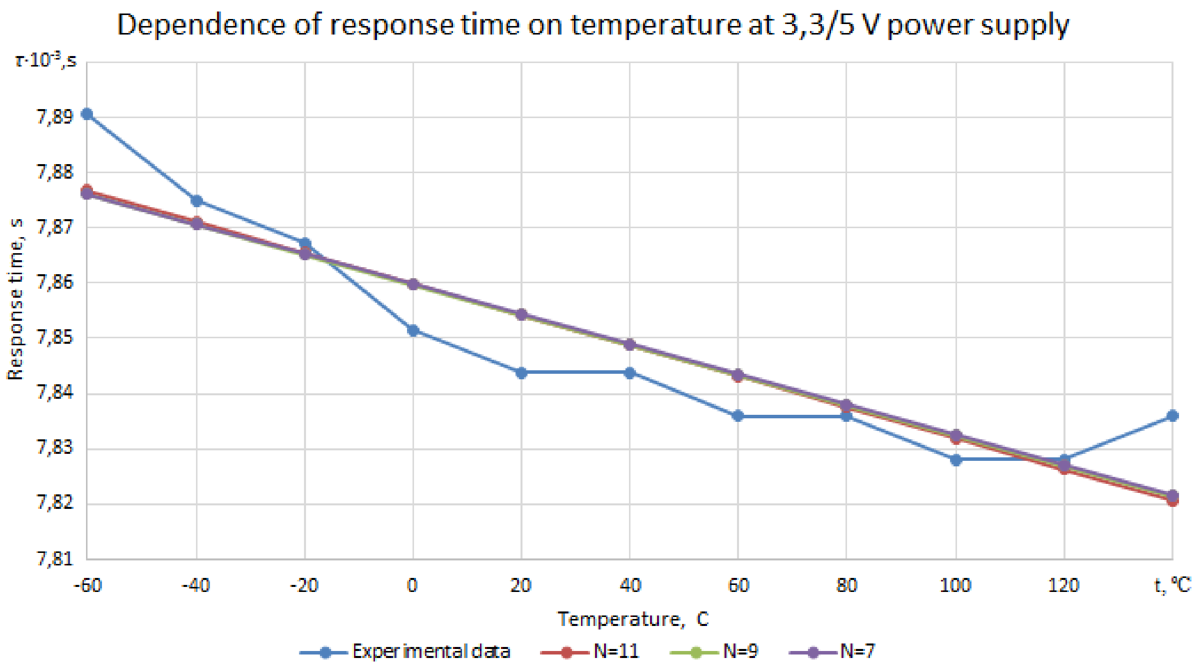

Fig. 5. The experimental and calculated dependencies of the response time on the temperature at the supply voltage 3.3 – 5 V

The models provided for calculating the coefficients are universal, i.e. they can be applied for any electronic units showing similar dependencies of the response time on the supply voltage, the time being in use and the ambient temperature. However, the coefficients themselves are unique for a specific electronic unit model and, likely, for each specimen as well. It might be, however, that the characteristics of different specimens of the same electronic unit vary within some small and acceptable range. Thus, to be able to apply the proposed model, one has to perform a set of experiments in order to obtain the results like those presented in Tables 1, 2 and 3 first and then to calculate the coefficients upon the conducted measurements.

It's worthwhile to store the coefficients in some reliable external memory chip of an embedded system in order to allow the latter to evaluate the reliability and applicability of the response time of its components. I.e., knowing its own properties and the properties of its components, an embedded system might be able to warn its operator that some operations slowed down and are no longer fast enough for normal operation.

VI. Conclusion

We've obtained three independent analytic dependencies of the difference between the nominal response time of an electronic unit and its actual value on the supply voltage, the ambient temperature and the time of being in use. The proposed dependencies do not allow us to find out the response time using all the three parameters (supply voltage, temperature, and age) simultaneously, i.e. each dependency shows the contribution of the only quantity. We are planning further investigation aimed at forming a unique function of three variables that would allow us to calculate the resulting response time.

The practical use of the proposed model is as follows. We use the derived formulas (3-4) independently and select the worst result (maximum $\Delta\tau$). Two other quantities can only worsen this result but never improve it. If the worst result proves that the system is no longer applicable, its operator should take some predefined actions. If not, there is not enough information to make any conclusions.

On the other hand, if we evaluate the increases in the response time contributed by each physical parameter individually, then sum them up and the sum does not make the response time go out of the expected range, we can conclude that the response time still fits the established norm. Here we rely on the fact that even if age, supply voltage and temperature do mutually impact each other, this influence has been already taken into account when drawing the dependencies between the response time and each of these parameters individually.

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