Annals of the University of Craiova, Electrical Engineering series, No. 47, Issue 1, 2023; ISSN 1842-4805 eISSN 2971-9852

DOI: 10.52846/AUCEE.2023.06

An Example of Performance Achievement Based on Errors Analysis for Low-Cost Circuits Design

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Abstract - **To create high-performance equipment, low-performance components, such as those from the old generations, can also be used. For example, if a conditioning stage (amplification/attenuation or filtering) is made with high-end components having increased performance, the costs are appropriate – using "classical" functional ones, the price of the equipment will become competitive. Low-cost devices may have features that do not make them attractive for inclusion in high-performance equipment but certain errors' analysis may lead to practical and useful results. A converter circuit from PWM pulses to DC voltage was used. Experimental determinations were made using several types of operational amplifiers and errors analysis and correction was carrying out.**

Cuvinte cheie: *componente electronice, analiza si corectia erorilor, erori sistematice, microcontroler, calibrare, câștig.*

Keywords: *electronic components, errors' analysis and correction, systematic errors, microcontroller, calibration, gain.*

I. Introduction

Measurement errors are often seen as the fault of the human operator, by not respecting certain conditions for carrying out the measurements. However, the error can also be the result of systemic operational problems, constantly affecting the measurement. The presentation of these aspects leads to the prevention and/or correction of errors.

Errors due to human operators include usage errors (performing an operation incorrectly or the incorrect version of the standard operating procedure) and measurement errors (making a measurement error in a process). The consequences of the presence of errors can be costly or even dangerous, [1].

The existence of digital process measurement chains can easily introduce various errors. Thus, errors can come from the multiplexing part, from sampling and from the analog-to-digital conversion, which can accumulate. The use of a microcontroller implies the existence of a program, and it can be easily modified and updated, correcting possible implementation mistakes.

Measurement systems have many error components involved in the measurement and even when known and corrected, the uncertainty (with a lower estimate than the initial one) affects the final measurement value, generating doubts about how well this result represents the measured quantity. Improper measurement can seriously affect quality-oriented companies because of the risks involved in making wrong decisions based on process control tools. Consequently, the effect of measurement uncertainty on the results must be carefully investigated, [2].

Systematic errors are easily observable and have a noticeable monotony (they can be constant or proportional to the measurement). Systematic errors are the first affecting the accuracy of a measurement. Sources of systematic errors result from observational error, imperfect instrument calibration, and environmental interference [3].

Systematic errors are different from random errors and they affect the aspect data which is reflected in obtaining false conclusions and interpretations. Measurements will deviate significantly from true values if systematic errors are present. A false positive conclusion or a false negative conclusion can be drawn about the relationship between the studied variables, [4].

A systematic error results in measurements of the same quantity differing in predictable ways. For each measurement, the result has the same sign and possibly the same amount compared to the true measurement. A systematic error can also be called a bias because the data is skewed in well-established ways that hide the true values. Offset errors and scale factor (gain) errors are two examples of quantifiable types of systematic errors.

Sources of bias can range from research materials to data collection procedures and analysis techniques. So they can come from all aspects of the measurement procedure.

Systematic errors can be mitigated by using procedures in the measurement process. For example, systematic errors can be observed in analog-to-digital and digital-to-analog conversions, but also in any other circuit where there is interference with an offset voltage, [5], [6].

For the detection of systematic errors, the obtained results may be compared with a known value or a theoretical value. Statistical methods can be used to analyze the data or the experimental setup can be changed to see if the error persists. Calibration of an instrument is another method of investigating systematic errors, which means comparing what the instrument records with the actual value of a known standard quantity. This procedure is done periodically for the instrument used and is done with a precise reference, [7], [8].

II. METHODOLOGY

A. Circuit design

The correction of systematic errors was analyzed for a circuit that transforms PWM pulses into direct voltage. The circuit has a mainly digital operation, using a microcontroller (PIC 18F452 from Microchip) and auxiliary circuits that use analog components such as operational amplifier and bipolar transistor. The design uses both digital and analog components; therefore it is possible to deal on both sides. Since we are talking about systematic errors, this is done only once, at the initial stage of setting up the device.

The structure of the considered device consists of a microcontroller and an output circuit, made around a low pass filter (LPF). The LPF is also a buffer for the output voltage, to isolate the output of the microcontroller and to protect it from overvoltage, Fig. 1.

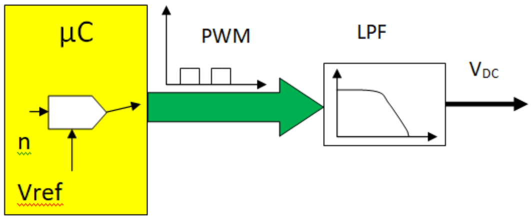

Fig. 1. The main components of the test equipment.

I used PWM, so that the method can also be used with microcontrollers that only have digital outputs.

The wiring diagram, in addition to the PWM signal generator microcontroller, consists of a 2nd-order low-pass filter, an output buffer and a bipolar power supply. A bipolar power supply was required because it is of interest to obtain a linear output voltage excursion, as much as possible (the transistor operates in the normal active region).

The entire device is powered from a 7V to 24V AC supply and the stabilized DC voltages are +12V and -5V to power the output buffer and +5V to power the microcontroller. It is not possible to feed the circuit with direct voltage, because it is not possible to obtain negative voltage. Additionally, a fuse and two diodes were provided which were used to protect the output against short circuit and overvoltage respectively, Fig. 2.

B. Application

The software of the microcontroller was developed in MPLAB IDE, using the specific assembly code, and was considered to display the information on the LCD, to observe the increment/decrement of the numerical values. The chosen resolution is 10 bits which corresponds to a step of ~4.88 mV. The execution speed is not critical, so any other microcontroller (or other brands) is suitable for using in the experiment - the only mandatory requirement is to have a PWM output mode.

A programming issue was displaying the decimal values corresponding to the 10-bits resolution of the digital-analog converter (DAC). That is because the microcontroller has an 8-bit memory configuration and the 10-bits

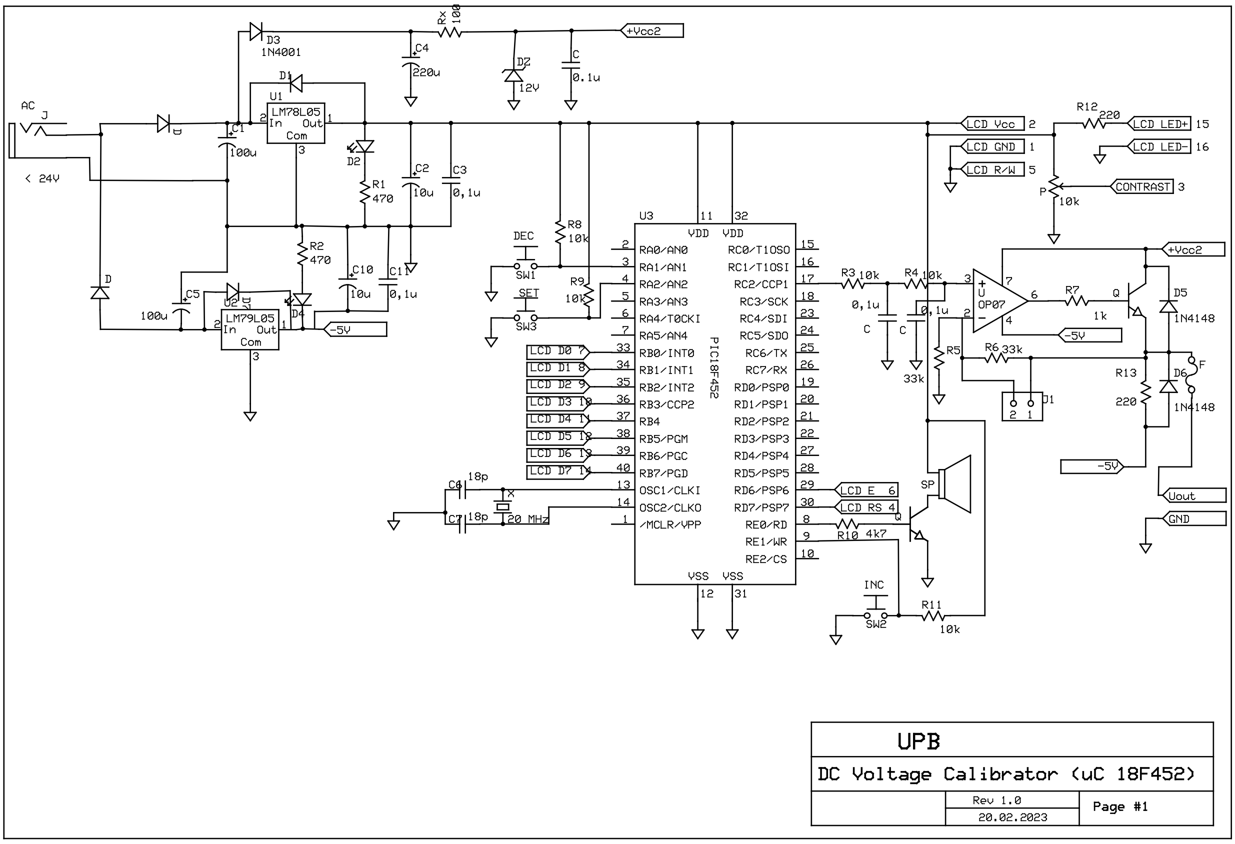

Fig. 2. The Complete schematics of proposed circuit.

DAC values are stored in two different memory locations (8-bits + 2-bits) - handling these extra 2-bits requires advanced programming skills. Other code sequences such as timing, initializing the LCD display, displaying characters on the LCD, and sending the number to the output port (via registers) were used, [9].

C. *Experimental setup*

Experimental determinations and all tests were performed using PIC 18F452 microcontroller. It is a multi-function microcontroller with PWM output and five I/O ports. It can operate in two DAC modes: 8-bit and 10-bit. In order to have the best resolution, the 10-bit option was used.

For testing the circuit, three different types of manufacturers for the operational amplifier of the output buffer were used, Table I.

TABLE I.
THE CONVERSION CHARACTERISTIC FOR DIFFERENT TYPES OF THE OUTPUT BUFFER

No.	Output voltage [V]		
	OP07	βA741	UA741
0	0.0012	0.0011	0.0023
1	0.0061	0.0061	0.0072
10	0.0505	0.0505	0.0516
50	0.2479	0.2479	0.2490
250	1.2357	1.2358	1.2367
500	2.4728	2.4731	2.4738
750	3.7125	3.7129	3.7136
1000	4.9548	4.9553	4.9559
1023	5.0692	5.0698	5.0703

As presented, the following parameters are established (initially):

- the step (4.88 mV),

- full-scale (depend by operational amplifier used (OP07 / βA741 / UA741) : from 0.0012 / 0.0011 / 0.0023 V to 5.0692 / 5.0698 / 5.0703 V),

- the percentage resolution (0.09669 / 0.09864 / 0.09669%) for this digital-to-analog converter.

The OP07 operational amplifier is a high-quality integrated circuit (lower offset voltage than the 741 family of circuits; 60 µV and 1 mV respectively).

The comparison of working frequencies is not relevant because both operational amplifiers work at approximately 20 kHz, a frequency far below the limit (e.g. 0.6 MHz for OP07).

The PWM module inside the PIC18 microcontroller uses a timer to control the signal frequency and duty cycle, [10]. The period of the generated PWM signal is given by (1).

$$PWM_{period} = (PR2 + 1) \cdot 4 \cdot TOSC \cdot TMR2_{prescale\ \_value} \quad (1)$$

Where PR2 is the value loaded into the period register and TOSC is the clock period of the peripheral clock.

To estimate duty cycle of signal must use register CCPR1L and CCP1CON value.

$$PWMDuty_{Cycle} = \frac{CCPR1L}{CCP1CON < 5:4 >} \cdot Tosc \cdot TMR2Prescale\_Value \quad (2)$$

Where CCPR1L represents 8 bits MSB and CCP1CON 2 bits LSB (4 and 5). These registers can be programmed to count up or down. The parameters for this project are summarized as follows:

- PWM_frequency= 19531.25 Hz
- TOSC= 51.2 us
- Timer used = Timer2
- TMR_prescaler_value= 124

To estimate the necessary correction, the error was computed, Table II.

TABLE II. ERROR OF SOME SAMPLED DATA

No.	Error [%]		
	OP07	βA741	UA741
0	0.02	0.02	0.05
1	0.02	0.02	0.04
10	0.02	0.02	0.04
50	0	0	0.02
250	-0.08	-0.08	-0.06
500	-0.13	-0.13	-0.11
750	-0.13	-0.13	-0.11
1000	-0.09	-0.08	-0.07
1023	-0.08	-0.07	-0.06

The used formula used is a typical one for D/A conversion, [6], [7],

$$\varepsilon = \frac{Vm - Vi}{Vref} \cdot 100 \quad (3)$$

Where *Vm* is the measured output voltage, *Vi* is the ideal output voltage (computed with D/A conversion formula) and *Vref* is the reference voltage, which in this case it is 5.0733 V.

$$\frac{N}{Nref} = \frac{V}{Vref} \quad (4)$$

The output characteristic and the error diagrams reveal differences between experimental results, Fig. 3, Fig. 4.

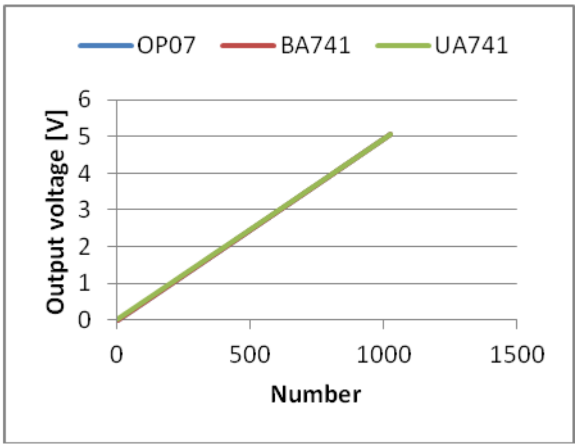

Fig. 3. The output characteristic with different operational amplifiers.

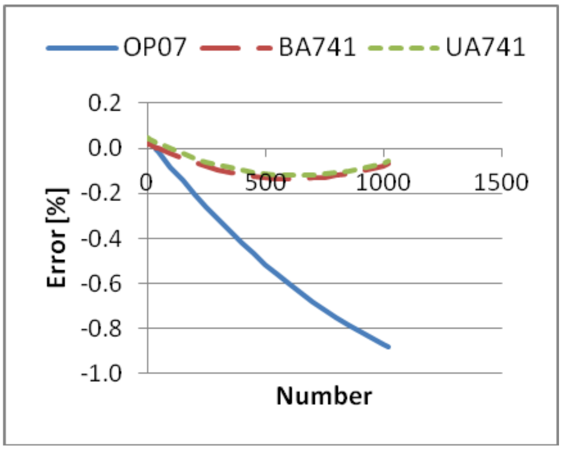

Fig. 4. The output characteristic error.

After errors' analysis and for performance improvement using error correction, we chose the circuit having the operational amplifier OP07 as output buffer, Table III.

The first step was the determination of the experimental output error, (5). The error plot shows that we are dealing with systematic offset errors and thus, they can be corrected by displacement. For βA741 and UA741 IC, Table IV and Table V present some computed correction.

The second step was to find the corresponding voltage for the error correction, (6).

The third step was to calculate the difference between the newest (preferred) voltage and the original voltage (measured voltage). Therefore, we considered using a constant voltage of approximately 0.003V in this case.

The meanings of the quantities are: ε correction is the necessary correction, in percent, based on minimum and maximum error computed with (1); Vcorrection is the expression of ε correction in volts and V is the theoretical/ideal voltage of D/A converter, from (2). The number 5.0733 represents the reference voltage of the DAC

$$\varepsilon correction = \varepsilon - \frac{(\varepsilon min - \varepsilon max)}{2} \quad [\%] \tag{5}$$

$$Vcorection = \varepsilon correction \cdot 5.0733/100 + V \tag{6}$$

This voltage resulting from the difference between the corrected and the measured value, 0.003V, is constant. This value is used to shift the output characteristic to reduce the maximum error from the initial rate, Fig. 5.

TABLE III
SOME COMPUTED CORRECTION FOR OP07

No.	OP07		
	New error (forced)[%]	Corresponding voltage [V]	Difference between the new output voltage and initial output voltage [V]
0	0.08	0.0042	0.0030
1	0.08	0.0091	0.0030
10	0.08	0.0535	0.0030
50	0.06	0.2509	0.0030
250	-0.02	1.2387	0.0030
500	-0.08	2.4758	0.0030
750	-0.08	3.7155	0.0030
1000	-0.03	4.9578	0.0030
1023	-0.02	5.0722	0.0030

TABLE IV
SOME COMPUTED CORRECTION FOR βA 741

No.			
	New error (forced)[%]	Corresponding voltage [V]	Difference between the new output voltage and initial output voltage [V]
0	0.0779	0.0040	0.0028
1	0.0787	0.0090	0.0029
10	0.0741	0.0534	0.0029
50	0.0550	0.2508	0.0029
250	-0.0228	1.2387	0.0030
500	-0.0723	2.4760	0.0032
750	-0.0725	3.7158	0.0033
1000	-0.0214	4.9582	0.0034
1023	-0.0128	5.0727	0.0035

Thus, the absolute maximum value is approximately 0.08%, from the initial value of 0.142%. Practically, the characteristic will be "centered", symmetrical to the axis.

This additional voltage can be generated internally, by software or externally, by applying a voltage to the operational amplifier that shifts the potential from the output. This correction can be done before using the device, into initial calibration phase.

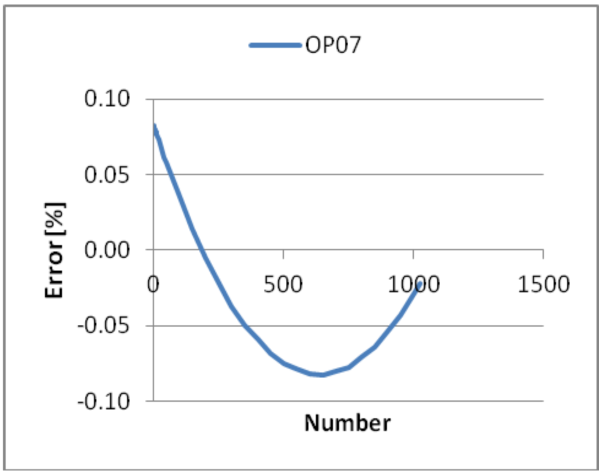

Fig. 5. New error after correction, OP07.

TABLE V
SOME COMPUTED CORRECTION FOR UA741

No.	UA741		
	New error (forced)[%]	Corresponding voltage [V]	Difference between the new output voltage and initial output voltage [V]
0	0.08321	0.0042	0.0030
1	0.08204	0.0091	0.0030
10	0.07744	0.0535	0.0030
50	0.05833	0.2509	0.0030
250	-0.02342	1.2386	0.0029
500	-0.07682	2.4757	0.0029
750	-0.07701	3.7155	0.0030
1000	-0.02792	4.9578	0.0030
1023	-0.02126	5.0722	0.0030

Program correction can be implemented if the digital-to-analog conversion step is smaller than the required correction. In our case it is 0.003V compared to 0.0049V.

New error plot for A741 and UA741 was generated after correction, Fig. 6, Fig. 7.

From Table IV, in case of use A741 operational amplifier, the difference between initial and new output voltage is not a constant but also difference is very small. This is because systematic errors it was not completely eliminated, having several causes.

Comparing initial errors, Fig. 4, with new errors, Fig. 5, Fig. 6, Fig. 7, it is obviously the efficiency of method proposed.

The error tends to be reduced by half, close to the error of the measuring equipment.

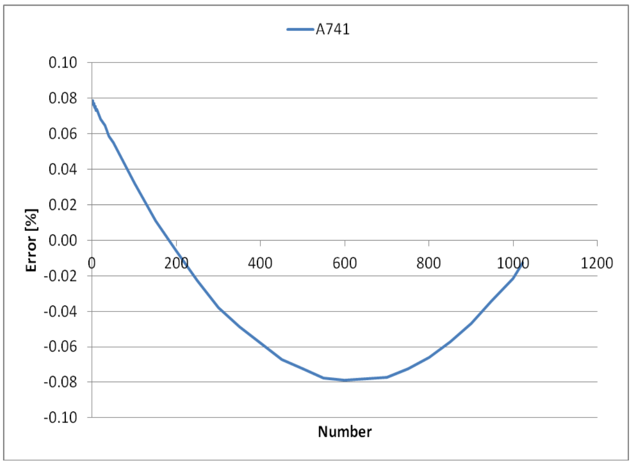

Fig. 6. New error after correction, A741.

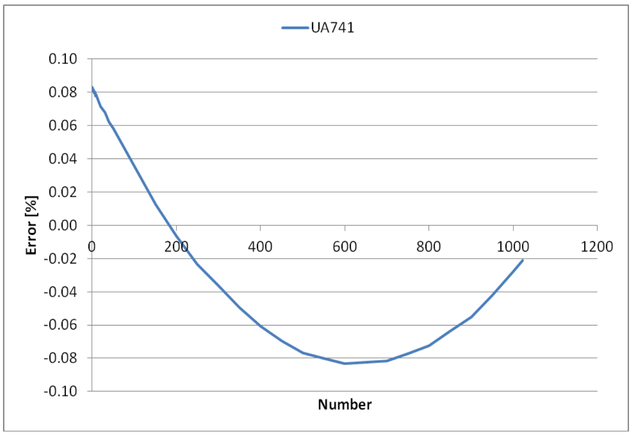

Fig. 7. New error after correction, UA741.

III. CONCLUSIONS

The presented method is useful when developing equipment or a device with low quality components, with reduced costs. After an initial analysis of the device/equipment performance, one chooses which method (software or hardware) is better to reduce systematic errors. For this, an imposed error is estimated, which is usually half of the original error. Then the voltage corresponding to this error is determined and finally it is checked if the differences, for the values of interest, are the same or very close. Depending on the results, it is decided whether the correction is made in the auxiliary electronic circuits of the microcontroller or internally, by changing the number used for conversion. There is also the possibility that the correction methods act on hardware and software simultaneously.

The solution used is chosen after analyzing the operation of the scheme, because the performance of the components used is important. If, for example, the compensation voltage exceeds the value of the converter, then the correction can be done by software. If this offset is less than the voltage step at the output, then the error correction can only be done by hardware.

Obviously, there is also the possibility of combining the two methods.

The experimental setup, Fig. 8, used in this case is a DC voltage generator, synthesized by the PWM technique, but one can imagine any other configurations, like signal generator or current source.

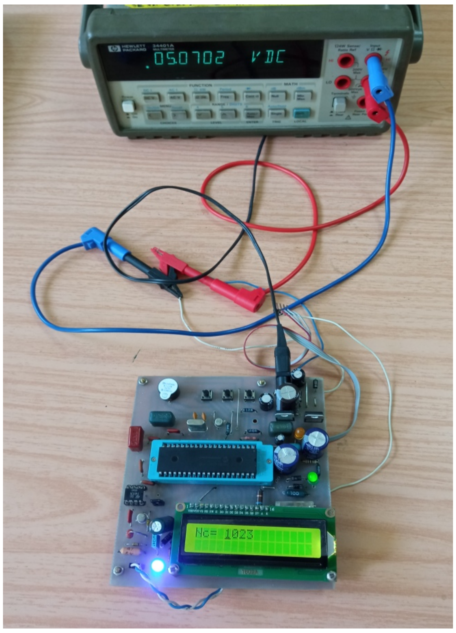

Fig. 8. Experimental setup.

A HP 34401A voltmeter with a measurement resolution of 0.1 mV was used to measure the voltages, which is adequate to validate the proposed method.

From the experimental data it is found the possibility of completely eliminating the systematic errors, when using the OP07 and UA741 integrated circuits. It's not the same when using A741, because it seems to be supplementary causes of systematic errors.

By using the microcontroller, additional functions can be performed, such as communicating with a computer or designing a more complex menu in the program through which certain settings of the operation of the microcontroller can be configured, including an adjustment of the offset of the generated output signal.

When testing the method one must take in consideration to correlate the device tested performance (in terms of errors) with the used measurement equipment.

To increase the degree of automation, a data acquisition board with appropriate performance (e.g. resolution/number of bits) can be used to allow the reading of the generated voltage, assistance from the automatic calculation and other possibilities (storage, filtering) of using digital information.

ACKNOWLEDGMENT

Source of research funding in this article: Research program of the National University of Science and Technology Politehnica, Bucharest.

Contribution of authors:
First author – 70%
First coauthor – 15%
Second coauthor – 15%

Received on July 23,2023
Editorial Approval on November 28, 2023

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