Study of Sensing Unit of Bionic Robotic Arm Based on Regression Model in Software Package Statistica

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Abstract. Nowadays, more and more automation tools are used in production and in industry. An important development of this direction are the elements of bionics, which allow replacing human labor with robotic devices. Despite the fact that robots are used in many places, their functionality is limited to small flexibility. It is proposed to use a bionic robotic arm, imitating a human hand and allowing you to feel the force of compression. Such a robotic mechanism will allow replacing human labor in the places where a greater accuracy is required and ordinary robotic arms are not acceptable. This manipulator will allow one operator to control two machines at the same time (earlier, when all operations were performed manually, this was not possible), which significantly reduces costs. In the paper a scheme of such a bionic robotic arm was developed and studied.

1. Introduction
The use of robots for welding, palletizing or packing has become common. But their use is much wider. All that a human hand can do can be repeated by a robot with its mechanical hand. And sometimes the robot may be more. No one will lift a load of 1000 kg [1-8]. And there are such robots. In places where, for example, rescue operations that require great physical strength from a person are performed, robotic exoskeletons are already used. In industry, robots are widely used for welding processes, product movement, fur processing, painting, assembly, etc. But to perform accurate operations, where any unnecessary effort can lead to collapse, human labor is still used. It is proposed to use a bionic robotic arm that imitates a person’s hand and allows it to be felt with the help of strain gauges [9-20].

This paper deals with the development of a unit for sensing such a robotic mechanism, as well as modeling in the Microcap program.

2. Materials and methods
In the framework of this work, a sensing unit, namely a strain gauge bridge and a differential measuring amplifier, is to be investigated. A schematic diagram of which is presented in Fig. 1.
The characteristics of the used strain gauge brand KSPL-7-60-E4 are presented in table 1.

| Parameter name                                      | Parameter value |
|-----------------------------------------------------|------------------|
| Operating gain (RCP), mV / V                        | 2.0              |
| Accuracy class (in accordance with GOST 30129)       | C3               |
| Type of Convertible Force                           | Stretching / compression |
| Maximum operating current, mA                       | 100              |
| Initial Transfer Ratio (NCP)                        | 2.5% of RCP      |
| Sensor body material                                 | Alloy steel      |
| Output impedance, Ohm                               | 352              |
| Insulation resistance, megohm                       | ≥5000            |
| Operating temperature range, ° C                    | –30 ÷ +50 ºC     |
| Permissible overload for no more than 1 hour        | 125% from NPI    |
| Breaking load                                       | 200% from NPI    |
| Recommended supply voltage, V                       | from 5 to 12     |
| Maximum supply voltage, V                           | 15               |
| Maximum load weight, g                              | 60               |
| Increment value, ohm                                | 8.8              |

According to table 1, the resistance of the selected strain gauge sensor is 352 Ohms, the increment value $\Delta R$ is 8.8 Ohms. To ensure high accuracy, a four-shoulder measuring bridge was selected, which is powered by direct current. General balance equation for a bridge:

$$R_1 \cdot R_2 = R_3 \cdot R_4.$$  

The voltage in the measuring diagonal at maximum load will be equal to:

$$U_v = U \cdot \frac{\Delta R}{R} = 15 \cdot \frac{8.8}{352} = 0.375 \text{ V}.$$  

Voltage in the measuring diagonal with a load of 10 g:

$$U_v = U \cdot \frac{\Delta R}{R} = 15 \cdot \frac{1.4}{352} = 0.06 \text{ V}.$$  

Voltage in the measuring diagonal with a load of 30 g:

$$U_v = U \cdot \frac{\Delta R}{R} = 15 \cdot \frac{4.4}{352} = 0.19 \text{ V}.$$  

Voltage in measuring diagonal load 50 g:

$$U_v = U \cdot \frac{\Delta R}{R} = 15 \cdot \frac{7.3}{352} = 0.311 \text{ V}.$$
Determine the gain, given that the expected voltage at the output of the strain gauge converter is 10 volts.

\[ K_\text{os} = \frac{U_{\text{out}}}{U_{\text{in}}} = \frac{10}{0.375} = 26.666 \approx 26 \]

To ensure the convenience of further calculations, round up the gain and take it equal to 26. This assumption can be compensated by adding a variable resistor to the amplifier circuit. The total gain \( K_{\text{os}} \) is formed from the product of the gain \( K_1 \) of the first stage, formed by amplifiers DA1 and DA2 and \( K_2 \) of the second stage, formed by amplifier DA3 (Fig. 6):

\[ K_{\text{os}} = K_1 \cdot K_2. \]

Take the gain of the first cascade equal to 2, and the coefficient of the second cascade equal to 13. The gain of the first stage is determined by the formula:

\[ K_1 = \frac{R_6 + R_7}{R_6}, \quad (1) \]

where \( R_6 \) and \( R_7 \) are assumed to be 10 kOhm;

Express and determine the value of the resistor \( R_5 \) from the formula (1):

\[ R_5 = \frac{R_6 + R_7}{K_1 - 1} = 20 \text{kOhm} \]

To fine tune the resistor \( R_5 \) divided into two series-connected - \( R_5 \) and \( R_p \).

The gain of the second cascade is determined by the formula:

\[ K_2 = \frac{R_8}{R_2}, \quad (2) \]

where \( R_8 \) is assumed to be 10 kOhm.

Determine the value of the resistor \( R_3 \), which follows from the formula (2):

\[ R_3 = K_1 \cdot R_6 = 13 \cdot 10 \cdot 10^3 = 130 \text{kOhm} \]

The value of resistor \( R_9 \) is taken equal to the value of resistor \( R_8 \):

\[ R_9 = R_8 = 10 \text{kOhm} \]

The value of resistor \( R_{11} \) is assumed to be equal to the value of resistor \( R_{10} \):

\[ R_{11} = R_{10} = 130 \text{kOhm} \]

The relative change in the resistance of the resistor when the ambient temperature changes (by 1 °C) characterizes the temperature coefficient of resistance (TCR). The resistance of the resistor at a given temperature can be found by the formula:

\[ R = R_T \cdot (1 + \alpha \cdot (T - 20)) \]

where \( R \) is the resistance at a given temperature; \( RT \) is the resistance of the resistor at room temperature (+20 °C); \( \alpha \) - temperature coefficient of resistance (TKS); \( T \) - set temperature, °C.

Calculate the change in resistance of the resistors at the maximum temperature deviations from the center of the plan:

\[ R_{5,\pm 50} = 20 \cdot 10^3 \cdot (1 + 300 \cdot 10^{-6} \cdot (50 - 20)) = 20.18 \text{kOhm}; \]
\[ R_{5,\pm 30} = 20 \cdot 10^3 \cdot (1 + 300 \cdot 10^{-6} \cdot (30 - 20)) = 19.7 \text{kOhm}; \]
\[ R_{6...R_9,\pm 50} = 10 \cdot 10^3 \cdot (1 + 300 \cdot 10^{-6} \cdot (50 - 20)) = 10.09 \text{kOhm}; \]
\[ R_{6...R_9,\pm 30} = 10 \cdot 10^3 \cdot (1 + 300 \cdot 10^{-6} \cdot (30 - 20)) = 9.85 \text{kOhm}; \]
\[ R_{10,R_1,\pm 50} = 130 \cdot 10^3 \cdot (1 + 300 \cdot 10^{-6} \cdot (50 - 20)) = 131.17 \text{kOhm}; \]
\[ R_{10,R_1,\pm 30} = 130 \cdot 10^3 \cdot (1 + 300 \cdot 10^{-6} \cdot (30 - 20)) = 128.44 \text{kOhm}; \]

It is necessary to build a model of the change in the relative error of the output voltage of the circuit described in the first chapter (see figure 2) depending on the supply voltage of the operational amplifiers \( U_{\text{pin}} \), the heating temperature of the resistors \( t \), the frequency of the input signal and the input voltage of the circuit \( U_{\text{in}} \) used. Therefore, we take as a response the relative error of the output voltage, and as the influencing factors we take the supply voltage of the operational amplifiers \( U_{\text{pin}} \), the heating temperature
of the resistors \( t \), the frequency of the input signal and the input voltage of the circuit \( U_{\text{in}} \). Thus, it is necessary to obtain a regression equation for a model of the form:

\[
\Delta = f(U_{\text{in}}, t, U_{\text{in}}, F_{\text{in}})
\]

You must choose a regression model of the object of study. Selecting a model means choosing the type of this function, writing down its equation. Then it remains to plan and conduct an experiment to estimate the numerical values of the coefficients of this equation. The polynomial model in its general form is determined by the expression:

\[
y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ij} x_i^2 + \sum_{i<j}^{k} b_{ij} x_i x_j
\]

where \( b_0, b_i, b_{ij} \) are estimates of the values of the coefficients of the equation, \( x_i, x_j \) are factors, \( y \) is the response, \( k \) is the number of factors.

An experiment in which all possible combinations of levels of factors are realized is called a full factorial experiment.

If the number of levels of each factor is equal to two, then we have the full factor experiment type \( N = 2^k \), where \( k \) is the number of factors.

Properties of a full factorial experiment of type \( 2^k \):

1) The first property - symmetry about the center of the experiment - is formulated as follows: the algebraic sum of the column vector elements of each factor is zero, or \( \sum_{i=1}^{N} x_{ji} = 0 \), where \( j \) is the factor number, \( N \) is the number of experiments, \( j = 1, 2 \ldots k \).

2) The second property, the so-called normalization condition, is formulated as follows: the sum of the squares of the elements of each column is equal to the number of experiments, or \( \sum_{i=1}^{N} x_{ji}^2 = N \). This is a consequence of the fact that the values of factors in the matrix are set to +1 and –1.

The third property is called the orthogonality of the planning matrix. The sum over the term products of any two column vectors of the matrix is zero, or

\[
\sum_{i=1}^{k} x_{ji} x_{w} = 0, \quad j \neq w, \quad j, w = 0, 1, 2, \ldots , k.
\]

The fourth property, called rotatability, that is, points in the planning matrix are chosen so that the accuracy of prediction of the optimization parameter values is the same at equal distances from the center of the experiment and does not depend on direction.

Perform the development of a mathematical model of the differential amplifier in accordance with the calculated data. As the environment of circuit simulation using the environment Micro-Cap 11. The developed model is presented in Fig. 2. The power supply of the prosthesis is 5-9 V and is usually permanent.

![Figure 2. Model of the investigated functional block in the environment of Micro-Cap 11.](image)

Fig. 2 presents the results of the simulation, talking about the health of the mathematical model. The calculated data coincide with the model.
As can be seen from the simulation (see figure 2.2), the output voltage of the amplifier $U_{out}$ corresponds to the calculated one. Determine the relative error of voltage measurement:

$$\Delta = \frac{U_{\text{calc}} - U_{\text{meas}}}{U_{\text{meas}}} = \frac{10 - 9.723}{5} \cdot 100 = 2.77 \%$$

where $U_{\text{calc}}$ - is the calculated voltage; $U_{\text{meas}}$ - measured voltage.

The magnitude of the error obtained can be considered acceptable, thus it can be concluded that the model is acceptable to use for the experiment.

To build a model of the first order, a full factorial experiment of type $2^k$ is used.

Zero levels of factors and intervals of their variation:

- $P = 50$ g;
- $h_1 = 20$ g;
- $t = 30 ^\circ C$;
- $h_2 = 55 ^\circ C$;

For the experiment with the number of factors equal to 2, we use the orthogonal central composition plan.

Fig. 4 presents the settings tab for the power supply of the operational amplifier.

**Figure 4.** Setting the parameters of the power supply of the operational amplifier.

Fig. 5 presents the interactive analysis launchpad in the Micro-Cap 11 environment.

**Figure 5.** Interactive analysis launchpad in the Micro-Cap 11 environment.
Figure 5. Transient Analysis Startup Window.

Processing of the obtained results will be performed using the software package Statistica 12. To analyze the obtained results and verify the adequacy of the model, you must specify the number of repeated experiments \( m = 3 \).

A central plan is used to build a second order model. A plan is called central if all points are located symmetrically relative to the center of the plan.

The orthogonal central composition plan (OCCP) includes: the core - the full factor experiment (FFE) plan, \( n_0 \) – central points of the plan, and two “star” points for each factor.

The total number of points is:

\[
N = 2^k + 2k + n_0,
\]

where \( n_0 = 1 \) for OCCP.

To build a mathematical model, we use OCCP. The matrix of the mathematical model of the OCCP is given in Table 2.1.

| Experience number | \( x_1 \) | \( x_2 \) | ... | \( x_k \) |
|-------------------|----------|----------|-----|----------|
| 1                 | +        | +        | ... | +        |
| 2                 | -        | +        | +   | +        |
| 3                 | +        | -        | +   | +        |
| 4                 | -        | -        | +   | +        |
| 5                 | +        | +        | +   | +        |
| \( 2^k-p \)       | -        | -        | ... | -        |
| \( 2^k-p+1 \)     | +\( \alpha \) | 0        | ... | 0        |
| \( 2^k-p+2 \)     | -        | 0        | 0   | 0        |
| \( 2^k-p+3 \)     | 0        | +\( \alpha \) | 0   | 0        |
| \( \ldots \ldots \ldots \) | \( \ldots \) | \( \ldots \) | \( \ldots \) | \( \ldots \) |
| \( \ldots \)     | 0        | 0        | +\( \alpha \) | 0        |
| \( 2^k-p+k \)     | 0        | 0        | ... | +\( \alpha \) |
| \( 2^k-p+k+1 \)   | 0        | 0        | ... | \( \alpha \) |

The compiled matrix for finding the regression equation of the 2nd order is given in Table 3.
Table 3. Experiment Planning OCCP.

| № | X | P | X | T | U_in, | U_out, | U_calc | K | K_received | δ |
|---|---|---|---|---|------|-------|-------|---|------------|---|
| 1 | + | 0 | + | 0 | 11   | 6     | 6     | 6 | 26,03215   | 0,123 |
| 2 | - | 1 | + | 0 | 6    | 1     | 6     | 6 | 26,35      | 1,346 |
| 3 | + | 0 | - | 0 | 11   | 8     | 6     | 6 | 25,97427   | 0,098 |
| 4 | - | 1 | - | 0 | 30   | 1     | 6     | 6 | 25,68333   | 1,217 |
| 5 | + | 0 | 0 | 0 | 11   | 4     | 6     | 6 | 25,99356   | 0,024 |
| 6 | - | 1 | 0 | 0 | 0    | 1     | 6     | 6 | 25,85      | 0,576 |
| 7 | 0 | 3 | + | 4 | 0,1  | 4,95  | 4,94  | 2 | 26,05789   | 0,222 |
| 8 | 0 | 3 | - | 3 | 9    | 1     | 6     | 6 | 25,95263   | 0,182 |
| 9 | 0 | 3 | 0 | 1 | 0    | 3     | 6     | 6 | 25,96315   | 0,141 |

Experiment planning is carried out using the Statistica 12 software environment. Statistica 12 is an integrated data analysis and management system. It is a tool for developing custom applications in business, economics, finance, industry, medicine, insurance and other areas.

We will conduct the experiment shown in Fig. 6-10.

![Figure 6. OCCCP table in the Statistica program.](image)

![Figure 7. Table assessing the adequacy of the model in the program Statistica.](image)

![Figure 8. Table of the resulting model in coded values.](image)
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Figure 9. Table of the resulting model in physical values.

| Factor   | Regr. Coeff. | Std. Err. | t(18) | p   | -95% Cnf Lim | +95% Cnf Lim |
|----------|--------------|-----------|-------|-----|--------------|--------------|
| Mean/Int. | 4.29055556   | 0.059666  | 71.9075 | 0.000000 | 4.165198     | 4.415913     |
| (1)Var1   | 0.67833333   | 0.036539  | 18.5647 | 0.000000 | 0.601568     | 0.755099     |
| (2)Var2   | 0.01851852   | 0.004060  | 4.6136  | 0.000242  | 0.009897     | 0.027048     |

Figure 10. Response surface for the resulting model.

Get the regression equation in physical values:

\[ y = 4.29055556 + 0.67833333Z + 0.01851852D. \]

3. Conclusion

Thus, from the model obtained, the linear nature of the dependence of the gain error on temperature and pressure is seen, the quadratic terms are insignificant and have little effect. The absence of quadratic terms in the regression equation proves the linear nature of the dependence.

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