Development of a control system with fuzzy tuning of values for the actuation setpoint

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Abstract. The article discusses the disadvantages of using fuzzy logic to correct the value of the PID controller coefficients in control systems. The disadvantages are related to the actuation setpoint, which knowingly doesn't provide optimal control during its implementation at the control object. It is proposed to use a fuzzy tuning of values for the actuation setpoint in the control system circuit based on the deviation between the measured values of the input action at the control object and the values accepted in the calculation by the mathematical model. Fuzzy tuning of values for the actuation setpoint provides that the control objects achieve the desired indicators without re-solving the optimization problem. The effectiveness of the proposed approach is demonstrated by the example of developing a control system for the electroplating process.

1. Introduction
Control systems are used to influence the object (technological process) in order to achieve the desired indicators [1-3]. The PID controller is the most common method of forming a control action as part of control systems. It should be noted that the PID controller isn't without drawbacks [4,5], including empirical selection of coefficients, an increased increment in the components of the high-frequency error signal, the appearance of high-amplitude pulses, and so on. There are articles in which fuzzy logic is used to correct the value of the PID controller coefficients [6-9]. However, the correction of the PID value coefficients mayn't necessarily provide optimal control when it is implemented at the control object. This is caused by the deviation between the real values of the input action on the control object and the values used in the calculation by mathematical model. Therefore, a repeated solution to the optimal control problem is required, which can turn out to be a long-time and laborious process. Using a fuzzy tuning of values for the actuation setpoint in the control system circuit is a way out of this situation.

The development of a control system with fuzzy tuning of values for the actuation setpoint is the purpose of article.

2. Materials and methods
Structural diagram of a control system with fuzzy tuning of values for the actuation setpoint is shown in figure 1.

The input action \(x(\tau)\) used in calculating the optimal value for the actuation setpoint \(r^*(\tau)\) according to the mathematical model, is transmitted to the control object.
The deviation $\Delta x(\tau)$ between the calculated value $x(\tau)$ and measured value $x_m(\tau)$ from the sensor is determined as:

$$\Delta x(\tau) = x(\tau) - x_m(\tau). \quad (1)$$

Deviation (1) is used as an input variable for the fuzzy tuning for the actuation setpoint.

The fuzzy tuning for the actuation setpoint consists of the following elements: 1) fuzzifier; 2) knowledge base; 3) inference unit; 4) defuzzifier.

The correction $\Delta r(\tau)$ of the setpoint value $r^*(\tau)$ found as an optimization result of the control object by a mathematical model is an output variable. The resulting setpoint value is determined as:

$$r(\tau) = r^*(\tau) - \Delta r(\tau). \quad (2)$$

The deviation between the output action $y(\tau)$ from the control object and the corrected setpoint value (2) is determined as:

$$e(\tau) = y_m(\tau) - r(\tau), \quad (3)$$

where $y_m(\tau)$ is measured value $y(\tau)$ from the sensor.

Deviation (3) and the coefficients $k = \{k_P, k_I, k_D\}$ are involved in the formation of the control action in the PID controller:

$$u(\tau) = k_P e(\tau) + k_I \int_0^\tau e(\zeta)d\zeta + k_D \frac{de(\tau)}{d\tau}, \quad (4)$$

where $k_P, k_I, k_D$ are the coefficients for the proportional, integral and derivative components of the controller.

### 3. Experimental part

Let us consider the development of a control system with fuzzy tuning of values for the actuation setpoint using the example of an electroplating process (control object).

The input action $x(\tau)$ contains:

$$x(\tau) = \{t(\tau), pH(\tau), H(\tau), L(\tau)\}, \quad (5)$$

where $t, pH, H$ is the temperature, acidity and electrolyte level; $L$ is the distance between the anode and cathode.
The output action $y(\tau)$ contains:
\[ y(\tau) = \delta(\tau), \]
where $\delta$ is the coating thickness, which is determined according to the Faraday's law:
\[ \delta = \frac{k}{\rho} \eta(t, pH, i_c) i_c \tau, \]
where $k$, $\rho$ is the electrochemical equivalent and density of the metal; $\eta$ is the metal output by current; $i_c$ is the current density; $\tau$ is the time of electrolysis.

The electroplating process mathematical model, which contains the equation of potential distribution and is solved by the finite difference method, was developed for the relationship of $y(\tau)$ on $x(\tau)$ in [10].

Direct measurement (7) is possible only after the end of the electroplating process and movement of the cathode from the electrolyte. Therefore, information on the optimal current density at the cathode is used as the output action (6) and the setpoint:
\[ y(\tau) \approx r^*(\tau) = [i_c(\tau)]. \]
which is determined according to Ohm's law in differential form:
\[ i_c = \frac{I}{S_c}, \]
where $I$ is the current; $S_c$ is the cathode surface area.

Current is determined according to Ohm's law in integral form:
\[ I = UR, \]
where $U$ is the voltage between the anode and cathode; $R$ is the electrolyte resistance, which is determined as:
\[ R = \frac{L}{\chi HW}, \]
where $\chi$ is the electrical conductivity; $W$ is the width of the electroplating bath.

Let the deposition of a nickel coating in a sulfate electrolyte on a cathode with $S_c = 4$ dm$^2$ in an electroplating bath with $W = 3$ dm be an example of a technological process. The constants and parameters that enter the mathematical model equations are taken from the reference book [11]. The approximation of the metal output by current is determined as:
\[ \eta(t, pH, i_c) = 0.01 \left( 0.1r^2 + 0.01r + pH \right). \]

The setpoint $r^*(\tau) = \{i_c = 1.75$ A/dm$^2\}$ is found as a solving result the problem of optimizing the electroplating coating uniformity for the input action $x(\tau)$=[$t = 24$ °C, $pH = 5.2$, $H = 2.5$ dm, $L = 2.5$ dm]. Maintaining the setting for $\tau = 31$ min should provide a coating thickness of $\delta_1 = 9.6$ μm according to the mathematical model. Let the vector components $x_m(\tau)$ measured using sensors (temperature, acidity, electrolyte level and distance between the anode and cathode) be described by dependencies:
\[ t_m(\tau) = 24 + \sin(\tau), \]
\[ pH_m(\tau) = 5 + 0.0005*(\tau - 31)^2, \]
\[ H_m(\tau) = 2.5 + 0.05\sin(\tau) - 0.0001(\tau - 31)^2, \]
\[ L_m(\tau) = 2.5 + 0.2\sin(\tau). \]

In the fuzzy tuning for the actuation setpoint the input variable is $\Delta x(\tau)$=$\{\Delta t(\tau), \Delta pH(\tau), \Delta H(\tau), \Delta L(\tau)\}$, the output variable is $\Delta r(\tau)$=$\{\Delta i_c(\tau)\}$. The following terms are defined for the $\Delta x(\tau)$ components: negative big (NB), negative middle (NM), zero (Z), positive middle (PM), positive big (PB). The following terms are defined for the $\Delta r(\tau)$ component: decrease fast (DF), decrease (D), don’t change (DNC), increase (I), increase fast (IF). The knowledge base contains 19 rules [12]. A fragment of the knowledge base has the following form:
1. if $\Delta t = \text{NB}$ and $\Delta pH = \text{NB}$ and $\Delta L = \text{NB}$ and $\Delta H = \text{NB}$ then $\Delta i_c = \text{DF}$.
2. if $\Delta t = \text{Z}$ and $\Delta pH = \text{Z}$ and $\Delta L = \text{Z}$ and $\Delta H = \text{Z}$ then $\Delta i_c = \text{DNC}$.
3. if $\Delta t = \text{PB}$ and $\Delta pH = \text{PB}$ and $\Delta L = \text{PB}$ and $\Delta H = \text{PB}$ then $\Delta i_c = \text{PB}$.

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The inference unit is implemented using the Mamdani algorithm. The defuzzification operation is implemented using to the center of gravity method. The dependences $\Delta r(\tau)$ on the components $\Delta x(\tau)$ are shown in figure 2.

![Figure 2](image.png)

**Figure 2.** The dependences $\Delta r(\tau)$ on the components $\Delta x(\tau)$
4. Results and discussion

The functioning results of the electroplating process control system are shown in figure 3. The values for the actuation setpoint without (line) and with (polyline) fuzzy tuning are shown in figure 3a. The increase in coating thickness is shown in figure 3b: 1) idealized electroplating process ($\Delta x(\tau)=0$ and $\Delta r(\tau)=0$); 2) electroplating process with fuzzy tuning of values for the actuation setpoint ($\Delta x(\tau)\neq 0$ and $\Delta r(\tau)\neq 0$); 3) electroplating process with only PID control law without correction of the actuation setpoint ($\Delta x(\tau)=0$ and $\Delta r(\tau)\neq 0$).

The coating thickness for case 1 is $\delta_1 = 9.6 \, \mu m$. The coating thickness for case 2 is $\delta_2 = 9.7 \, \mu m$. The coating thickness for case 3 is $\delta_3 = 8.9 \, \mu m$. The relative deviations from case 1 are 1.0% and 7.2%, respectively. The result obtained indicates the effectiveness of the use a fuzzy tuning of values for the actuation setpoint in the control system circuit.

5. Conclusions

The considered approach is relevant when objects control that are described by mathematical models with distributed coordinates. The optimizing such control objects in real time is usually impossible and is a long-time and laborious process. In this case, the use of a fuzzy tuning of values for the actuation setpoint (based on subject area knowledge) is a promising direction for control objects to achieve the desired indicators without re-solving the optimization problem.

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