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Image autofocusing in optoelectronic systems based on a fuzzy PID controller

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The problem of improving the accuracy and speed of automatic focusing systems in optoelectronic systems (OES) is considered. It is shown that the application of classical PID controllers is limited by nonlinearities of drives and non-stationarity of observed scenes. A structure of an adaptive system using fuzzy logic for dynamic tuning of the PID controller coefficients is proposed. The choice of the Tenengrad contrast measure function and the Orange Pi 6 Plus hardware platform for real-time algorithm implementation is substantiated. The expected performance indicators of the proposed approach are given.

Keywords: autofocus, optoelectronic system, fuzzy controller, PID controller, focus measure function, image processing, Orange Pi, adaptive control.

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Introduction

Modern optoelectronic systems (OES) impose stringent requirements on image quality, the key condition for which is precise focusing (autofocus). The task is complicated by the nonlinearities of the lens drive (backlash, dry friction) and the variability of the characteristics of the observed scenes (illumination, contrast), which makes the control object non-stationary. A promising direction for operation under such conditions is the application of adaptive control methods [1, 2].

Traditional PID controllers, tuned to a single operating point, lose efficiency when the dynamics of the object change. Extremum-seeking controllers are prone to oscillations near the focus point and have low response speed. An alternative effective approach is the application of fuzzy PID controllers [3], which allow real-time adaptation of control parameters, ensuring robustness to nonlinearities and external disturbances. The effectiveness of such an approach for autofocus tasks has been confirmed experimentally [2].

The aim of this work is the theoretical substantiation and development of the structure of an autofocus system structure based on a fuzzy PID controller using a modern element base for video data processing.

Problem statement and selection of the focus evaluation function

The autofocus process can be represented as the task of finding the lens position x^* at which the sharpness evaluation function $F(x)$ is maximal: $x^* = \arg \max F(x)$. The control error $e(t)$ is indirectly determined through the deviation from this maximum. The dynamics of the drive, for example, a DC motor, can be described by the transfer function $W(s) = \frac{k}{s(T_ms + 1)}$, where k is the gain coefficient, and T_m is the electromechanical time constant. This model does not account for nonlinearities such as backlash, which requires the application of more complex control algorithms [2, 4].

The performance quality of the system directly depends on the choice of $F(x)$. A comparative analysis of methods showed that for real-time tasks, the most applicable is the **Tenengrad gradient method**, which provides a good compromise between accuracy and computational complexity. The fundamental justification of this method is presented in [5]. Its effectiveness for images close in nature to those obtained in OESs has been confirmed in later studies [6]. The algorithm consists in convolving the image $I(x, y)$ with Sobel operators to obtain the horizontal $G(x)$ and vertical $G(y)$ gradient components, to calculate the gradient magnitude $S(x, y) = \sqrt{G_x(x, y)^2 + G_y(x, y)^2}$ and to summing it over the analysis region $M \times N$:

$$F_{\text{Tenengrad}} = \sum_{x=1}^M \sum_{y=1}^N S(x, y).$$

Development of a fuzzy PID controller

The proposed system (Fig. 1) is built according to a two-level scheme. The lower level is a classical PID controller, generating a control signal $u(t)$ to the drive. The upper level is a fuzzy corrector that dynamically changes the PID controller coefficients: ΔK_p , ΔK_i , ΔK_d . The resulting coefficients are determined as: $K_p = K_{p0} + \Delta K_p$ etc., where K_{p0} are the baseline values. The theoretical foundations of fuzzy control are set out in [3], and the successful application of a similar structure for autofocus tasks has been demonstrated in [2, 4].

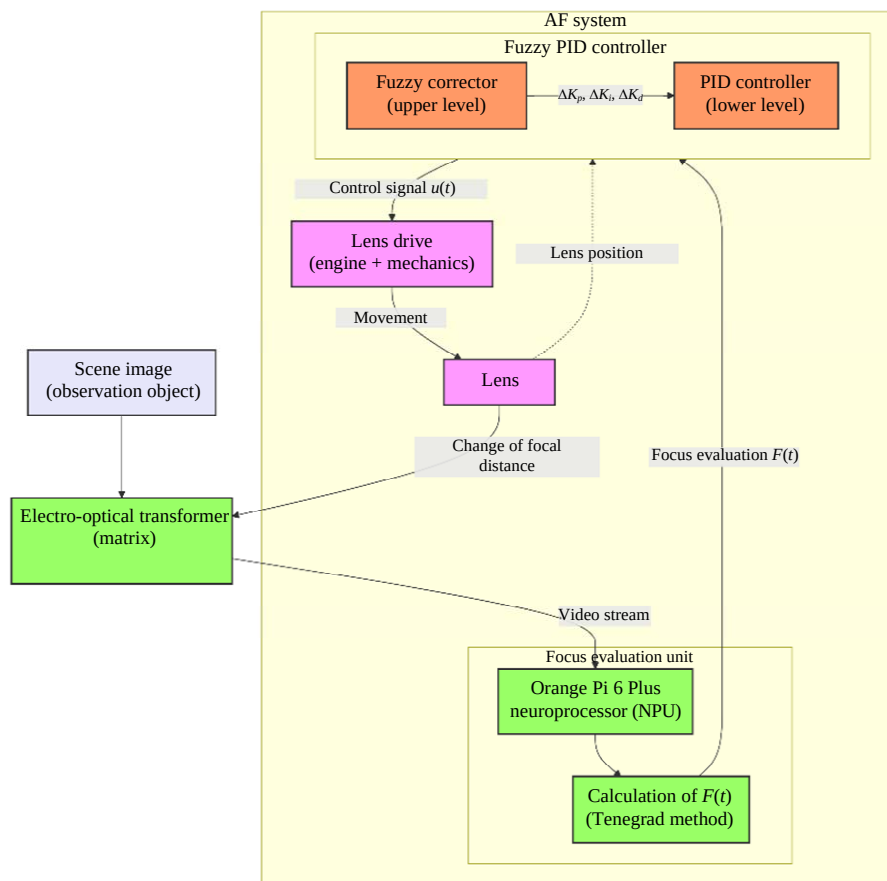


Fig. 1. Structural diagram of the autofocus system with a fuzzy PID controller

The input crisp variables – error e and its rate of change $\dot{e}$ – are transformed into linguistic variables with seven terms: NB (negative big), NM, NS, Z, PS, PM, and PB (positive big). Triangular-shaped membership functions are chosen. The fuzzy rule base (table) was

developed on the basis of empirical knowledge about tuning PID controllers, adapted for the autofocus task. To obtain crisp values of the correction coefficients, the centroid method is used. A similar approach to forming the rule base was used in [2].

Table

Fragment of the rule base for ΔK_p correction

$e/\dot{e}$	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PM	PM	PS	Z	Z
Z	PM	PM	PS	Z	NS	NM	NM
PB	Z	Z	NS	NM	NM	NB	NB

Hardware implementation and expected results

To implement the system, it is proposed to use an Orange Pi 6 Plus single-board computer with a CIX CD8180 SoC. A key advantage is the built-in neural processing unit (NPU) with a performance of 28.8×10^{12} operations per second, enabling hardware acceleration of the Tenengrad function computation (convolution with Sobel kernels). The following load distribution is planned: NPU – preprocessing and computation of $F(t)$; CPU (high-performance cores) – operation of the fuzzy controller.

Given that the work is at the stage of theoretical development, quantitative performance indicators are estimated as projected. It is planned to conduct simulation modeling in MATLAB/Simulink for a drive model with a "backlash"-type nonlinearity. It is expected that, compared with a classical PID controller, the fuzzy PID controller will allow overshoot to be reduced by 20–30 % and settling time to be reduced by 25–35 % (Fig. 2), which is consistent with the results obtained in [2, 4].

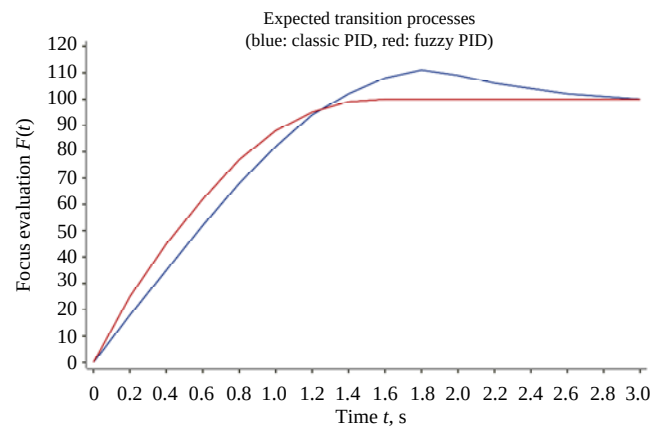


Fig. 2. Expected transient processes for classical and fuzzy PID controllers.

Conclusion

In this work, an analysis of the autofocus problem was carried out, and the feasibility of applying adaptive control methods was substantiated [1, 2]. A contrast evaluation function (Tenengrad method) was selected, based on fundamental [5] and modern [6] studies, and the structure of a fuzzy PID controller was developed [2, 3]. The choice of the Orange Pi 6 Plus hardware platform was justified; its use will enable real-time implementation of the algorithms. Projected performance indicators were formulated. Further research will be directed toward simulation modeling and experimental validation on a developed test bench.

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