Buletinul Ştiinţific al Universităţii "Politehnica" din Timişoara

Seria ELECTRONICĂ şi TELECOMUNICAŢII
TRANSACTIONS on ELECTRONICS and COMMUNICATIONS

Tom 51(65), Fascicola 1, 2006

Feedback control design for the image segmentation level in an image processing system

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Abstract – Inclusion of closed-loop control to overcome the problems of traditional open-loop image processing is proposed. The basic principles and features of feedback control in image processing are illustrated by the example of the recognition of 3D characters on a metallic surface. The feedback control for improving the image segmentation and consequently the character recognition in an unevenly illuminated image is presented.
Keywords: image processing, character recognition, local thresholding, feedback control

I. INTRODUCTION

The improvement of robustness and reliability of vision algorithms is a key issue in computer vision. A number of methods for robust image processing have been developed over recent decades [1]. Their common characteristic is development of vision algorithms with adaptive parameters in order to find the optimal parameters that can cope with the challenges of a particular real-world application. Most of those methods are open-loop so that they are characterised by the significant disadvantage that the low- and high- components of a vision system do not interact, which often leads to nonrobust performance under changing environmental conditions. Recently, a few closed-loop robust image processing systems have been published [2]. The basic idea is to take the output of high level processing and to use it as a feedback to influence the performance of the lower level image processing. Some of those systems consist of optimization algorithms [3] while some are characterized by usage of control techniques [4]. In contrast to Active Vision and Visual Servoing systems, which use the image processing to provide visual feedback information for closed-loop control [5], there are only a few publications dealing with the usage of control techniques in image processing [4][6]. The intention of this paper is to give an additional contribution to the topic.

The authors that have used classical and modern control techniques to solve image processing problems used them for improving the reliability of applied processing techniques. E.g. in [4] control ideas were used to improve sub-pixel analysis in pattern matching. In those publications the image quality is taken for granted. The assumption is that the image at the high level of an image processing system, usually concerning the object recognition, is of a quality good enough for successful feature extraction. In contrast, in this paper as well as in [6] the closed-loop control of image quality at different levels of image processing, including image acquisition, is considered. Namely, due to numerous external disturbances the images at different stages of processing, which are arranged sequentially starting from original (not-processed) image, are often of bad quality so image information is lost during the sequence of processing stages. By inclusion of feedback image quality control the high processing level is supported by reliable data from the lower levels of image processing. The idea behind this is that feedback has natural robustness against system uncertainty and ability to provide disturbance rejection, which is a fundamental concept in control theory [13]. The paper treats the full process of designing a feedback control system that consists of the following steps:

1. the selection of actuator and controlled variable,
2. the selection of a control structure,
3. controller design.

The paper is organized as follows. The key principle of the inclusion of feedback structures in image processing is given in Section II. Specifics, as well as the benefit of the closed-loop control in image processing, are discussed more detailed in Sections III and IV through the demonstration of results achieved for recognition of characters on metallic surfaces. Our feedback mechanism treats the image acquisition as the essential image processing step bearing in mind the influence of the quality of original image on the subsequent processing, which is different from other published results on feedback structures in image processing [2][7]. Besides the image acquisition control, aiming at improvement of the quality of original image, the inclusion of feedback control at the segmentation level of image processing is considered. The full process of designing the threshold adjustment closed-loop is presented in Section IV. The method based on independent

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feedback control loops is suggested for the solution of the problem of character recognition in an unevenly illuminated image. The comparison of performance of proposed method of closed-loop parameter adjustment to the performance of traditional open-loop adaptive thresholding method is given in Section V.

II. CLOSED-LOOP CONTROL IN IMAGE PROCESSING

In a traditional image processing system, processing steps are arranged sequentially as shown in Fig. 1. This arrangement causes a lot of problems. Most important is the unreliability due to the high sensitivity to imaging conditions. That is, due to numerous external influences like illumination conditions, imaging system and imaged objects characteristics, the original image is often of bad quality. If its imperfections are introduced in the standard sequential processing steps then the results of the subsequent steps become unreliable. Nevertheless, in many real-world applications vision engineers will accept the images as given and use traditional preprocessing methods to improve the image quality. This is time-consuming and the results are of low accuracy due to the image information loss during the image acquisition. A further factor is that traditional image processing systems are not flexible since the processing algorithms are mostly *ad-hoc* suffering from the subjective tuning of parameters. Later, together with the fact that the processing at lower levels is performed regardless of the requirements of the following steps, leads to low-robustness of the overall system even in a case of reliable input image data. These problems of traditional open-loop image processing system can be overcome by the introduction of feedback structures at all levels of image processing as proposed in Fig. 1.

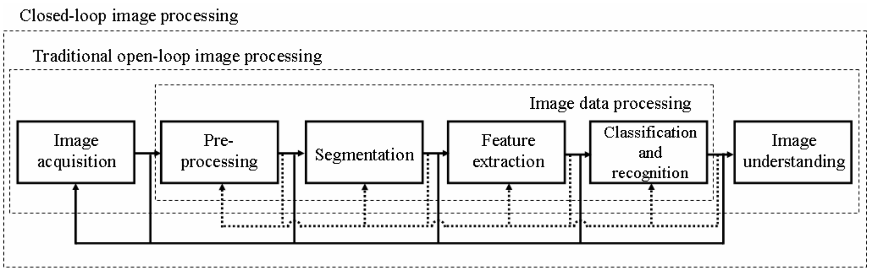


Fig. 1. Block-diagram of standard open-loop and closed-loop digital image processing

It is possible to include two types of closed-loops in a standard image processing system. The first one can be named *image acquisition closed-loop*. Here, the information from all subsequent stages of image processing may be used as feedback to control acquisition conditions (solid lines in Fig. 1). The aim is to provide a "good" image for the subsequent processing steps. The second type of closed-loop can be realized as the feedback between the quality of the image, representing the input of a higher processing level, and the parameters of image processing at lower level as represented with dashed lines in Fig. 1. This closed-loop adjusts parameters of the applied processing algorithm according to requirements of the subsequent image processing step and so can be named *parameters adjustment closed-loop*.

A. *The choice of actuator and controlled variables*

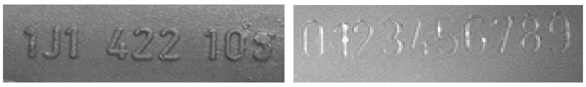
The closed-loop control in image processing differs significantly from the usual industrial control, especially concerning the choice of actuator and controlled variables. Generally, the actuator variables are those that directly influence image characteristics. Hence, for the image acquisition closed-loop, depending on the application, the actuator variables can be camera's parameters or the illumination condition. For the second type of closed-loop the actuator variables are the parameters of applied processing algorithms (e.g. coefficients and size of filter masks). However, the choice of controlled variable is not a trivial problem. This variable has to be appropriate from the control as well as from the image processing point of view. From the image processing point of view, a feedback variable must be an appropriate measure of image quality. A basic requirement of the control is that the quality of the image has to be measured so that the control variables can be changed to optimize it and it should be possible to calculate it easily from the image.

The problem of identifying which image data are good or bad has become a serious issue in the vision community [8]. To answer the question "what is the image of good quality?" is quite a difficult problem since the image quality depends on the interpretation of the image context. If the image of a "top fashion model" is considered, a good image may hide some details like e.g. imperfect skin. For a surgical endoscope a good image is one showing the organ of interest in all details clearly for human interpretation. Besides, in the computer vision context the way in which the computer "sees" is of importance. Since the correct image understanding highly depends on the result of object recognition as last step in the processing steps chain (Fig. 1), it turns out that *a "good" image is one on which the subsequent steps work well.* Hence, the original image is suitable for further processing if it is not saturated. The resulting image of the preprocessing step is "good" if it has good contrast. The output image at segmentation level is "good" if the image areas corresponding to objects of interest are correctly segmented, etc.

The selection of actuator and controlled variables, known also as *input/output selection*, as well as the selection of control structure highly depends on the application. In the following, these selections representing the typical steps in the process of designing a control system is presented for the case of character recognition in industrial environment. The authors are of opinion that despite of application dependence, once a input/output pair is found and control system is designed the framework for the inclusion of proven error based control techniques in different image processing applications is provided.

III. AN EXAMPLE: RECOGNITION OF CHARACTERS IN INDUSTRIAL ENVIRONMENT

Automated reading of human-readable characters, known as optical character recognition (OCR) [9], is one of the most difficult tasks for computer vision. Besides the common problems concerning the nature of text information to be recognized, in various industrial applications there are numerous specific challenges that should be met. In the automotive industry, that represents one of the most frequent and important application area of the OCR, there is a great variety of identification marks to be detected.



embossed characters scratched characters

Fig. 2. Different types of codes on metallic surfaces to be detected

Scratched or embossed (Fig. 2) marks of work pieces, representing surface deformations, are required in many production processes as durable markings, resistant to subsequent processing. Because of their 3D structure, it is often difficult to illuminate, to segment and, consequently, to detect them. Usage of directional front lighting is a good way to visualize surface deformations since the characters appear bright in contrast due to the reflection from the characters edges [11]. Depending on the quality of the marking process, the depth of the characters on differently colored and processed surfaces can vary demanding a variable illumination even for the same characters due to different reflection conditions. Hence, to find the optimal illumination is of major significance for characters detection. To cope with the need for illumination adaptation the inclusion of feedback control in standard open-loop OCR system is suggested as presented in the following. This inclusion has been investigated within the experiment of imaging differently colored metallic plates with scratched characters on them in variable illumination conditions [10].

A. Feedback structures for improvement of character recognition on metallic surfaces

We consider the classical structure of an OCR system [9] consisting of two sections: image acquisition and image data processing. Processing consists of usual steps: segmentation of characters, their binarization, classification and recognition. The novel difference between our configuration and other traditional systems lies in the extension with two control loops as shown in Fig. 3. The idea behind is to provide a basis for the classification to be supported by reliable data from the lower levels of image processing.

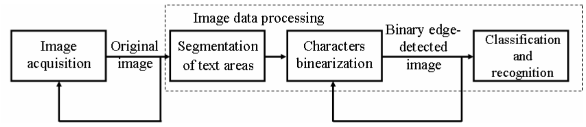


Fig. 3. OCR system with included feedback control

A sequential arrangement of control loops has been chosen since the image acquisition closed-loop is necessary to provide the optimal illumination which yields the original image of "good" quality suitable for the subsequent segmentation. This closed-loop, realized as feedback between the quality of the original image and the illumination condition, as a crucial factor for the image acquisition, is described in details in [12]. In this paper, the emphasis is only on the threshold adjustment closed-loop realized as the feedback between the quality of binary edge-detected image and the threshold as a parameter determining the success of characters binarization at image segmentation level. Its control goal is to give a "good" image input for the classifier, i.e. the binary image containing the "full" clearly separated characters that resemble the characters used for the training of the classifier so that all can be recognized. The second closed-loop is initialized once the image of good contrast is achieved by the image acquisition closed-loop.

IV. THRESHOLD ADJUSTMENT CLOSED-LOOP

As shown in Fig. 3, the segmentation of characters consists of two image processing operations: edge-detection and thresholding. Bearing in mind that the image acquisition closed-loop provides original image of good quality, the assumption that the edges of characters are correctly segmented by chosen Sobel filter [11] can be taken for granted. Hence, the eventual success or failure of subsequent characters classification highly depends on the thresholding step. Thresholding is an image point operation which produces a binary image from a gray scale image (in our system from the gray scale edge-detected image). Too high threshold yields a very small number of black pixels and so, in the case of white background and black characters, leads to loss of information on characters to be detected. In contrast, a low threshold yields a large number of black pixels giving noisy characters. That is why the adequate determination of the threshold and its adaptation to environmental changes is of major importance for character recognition. Since it is very difficult to estimate what is optimal threshold without any feedback information on the result of image binarization, thresholding in standard open-loop image processing gives often poor results. To determine the threshold providing a binary image with maximum information on characters it is suggested to apply the proven error based control techniques by the closed-loop shown in Fig. 4.

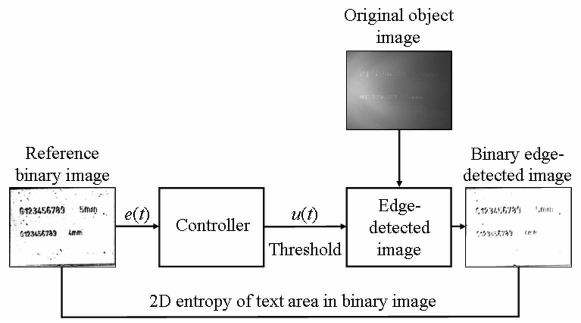


Fig. 4. Threshold adjustment closed-loop

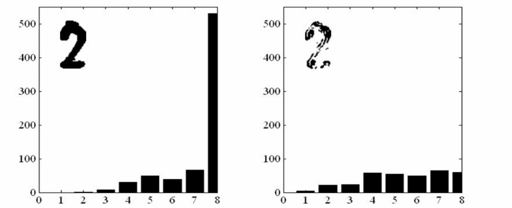
A. *The selection of actuator and controlled variable*

In the proposed closed-loop image segmentation system the threshold value, as parameter determining the quality of binary image, is considered as the actuator variable. The more compact are black pixels that form the characters to be recognized, the binary image is of better quality. Hence, the measure of connectivity of black pixels in text area is naturally imposed as controlled variable. We introduce the two-dimensional (2D) entropy as a connectivity measure:

$$S = -\sum_{i=0}^{8} p_{(0,i)} \log_2 p_{(0,i)} \,, \tag{1}$$

where $p_{(0,i)}$ is the estimate of the probability of occurrence of a pair (0,*i*) representing the black pixel surrounded with *i* black pixels ($i \in [0,8]$ for the 8-pixel neighbourhood).

Figures 5(a) and 5(b) show respectively the images of the "good" numerical character "2" and the "broken" one with the corresponding histograms of distribution of pairs (0,*i*) found in the characters images.



(a) (b)

Fig. 5. "Full" (a) and "broken" (b) numerical character "2" with corresponding histograms of distribution of pairs (0,*i*)

Obviously, histogram of the "full" character is narrow in contrast to histogram of the "broken" one. This is an expected result since the number of different pairs (0,*i*) in the image of "good" character is smaller than in the image of "noised" one, but the estimate $p_{(0,i)}$ is larger. Since a random variable X with a large probability of being observed has a very small degree of information $-\log p(X)$, according to (1) the 2D entropy of a "good" character is to be quite smaller than the 2D entropy of a "broken" character. The results 1.066 and 2.775, for shown "full" and "broken" character respectively, confirm the previous statement. This provides a basis for the use of 2D entropy as a measure of the quality of a binary image containing the characters to be detected.

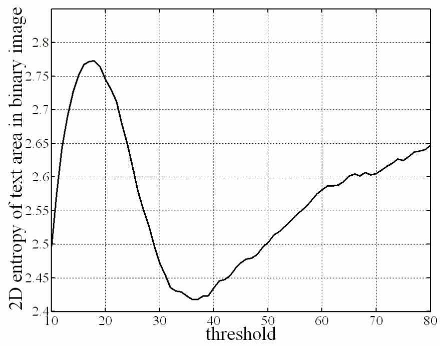


Fig. 6. 2D entropy of text area vs. threshold value

Fig. 6 shows the changing of 2D entropy of text area in binary image with changing of the threshold value. Evidently, 2D entropy of text area is *sensitive* to the chosen control variable across the available operating range. Also, it is obvious that there is *one-to-one steady state mapping* between these two variables and that it is possible to achieve the *global minimum* of *S* by changing the threshold. The satisfied prerequisites for successful control action prove the pair "threshold – 2D entropy of text in binary image" as a good pair "actuator variable - controlled variable". The idea behind is to drive the actual 2D entropy to the reference value and so to achieve a binary image suitable for recognition.

B. *Choice of the control structure*

Even though smaller 2D entropy means better quality of text to be recognized, the global threshold corresponding to minimal 2D entropy of whole text area will not yield good recognition result. As it was said in Section III, the considered metallic plates were illuminated using point lighting in order to detect the characters edges. The drawback is an unevenly illuminated image. Due to that, the regions of interest (ROIs) in image (in our case 4 text regions) are of different brightness. Hence, the global optimal threshold is not necessarily the optimal threshold for the particular region when consider the number of recognized characters. The 2D entropies of all ROIs in considered image of metallic plate, with 4 strings of scratched characters on it, that correspond to global i.e. to optimal local thresholds are shown in Table 1.

Table 1

	ROI1	ROI2	ROI3	ROI4
Global threshold	38	38	38	38
2D entropy	2.280	2.492	2.383	2.416
Optimal local threshold	38	20	34	26
2D entropy	2.280	2.284	2.339	2.156

The solution of the problem of global thresholding is to perform so-called local adaptive thresholding. The assumption behind this is that smaller image regions are more likely to have approximately uniform illumination, thus being more suitable for the thresholding. In the literature there are different local adaptive thresholding methods which basically divide an image into an array of subimages and then find the optimum threshold for each subimage by investigating its histogram [14]. Those methods are open-loop and so suffer from all problems of standard open-loop image processing mentioned in Section II. To overcome those problems we propose the feedback control structure consisting of four independent control loops as shown in Fig. 7. The idea behind is to drive separately the actual 2D entropy in each ROI (y_i, $i = 1,..,4$) to the given reference value (r_i, $i = 1,..,4$) and so to achieve a binary image with all text regions suitable for recognition.

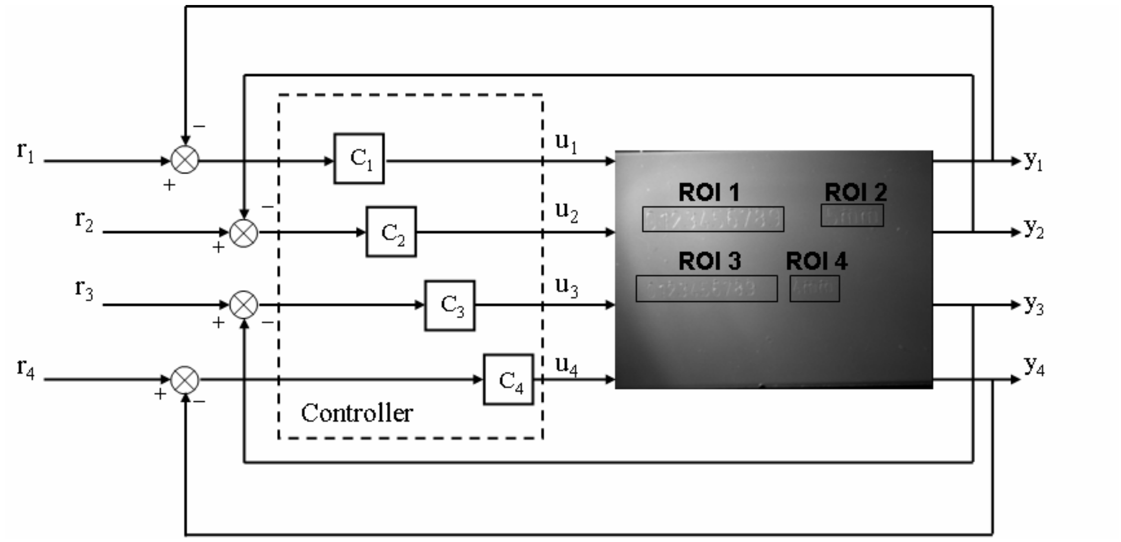


Fig. 7. Feedback control of local image thresholding

C. *Controller design*

The design of proposed control system involves two steps:

1. the choice of input/output pairings
2. the design (tuning) of each controller C_i.

In each individual loop the pair "threshold - 2D entropy of text in ROI" is chosen as appropriate "actuator variable u_i – controlled variable y_i" pair. The justification of this choice has been discussed in the previous section. In the following, the second step of feedback control system design is shortly presented.

The difficulty of suggested control system lies in the tuning of parameters of each controller C_i (here $i = 1,...,4$). This difficulty is emphasised in an image processing system bearing in mind that the main goal of inclusion of closed-loop control is to avoid "trial and error" tuning of many image processing parameters. Hence, the control design objective was to minimize the tuning problem subject to the achievement of accuracy and stability specifications in the face of uncertainty. Therefore the PI controllers with the same proportional *Kp* and integral *Ki* gain for each individual loop have been considered. The controller parameters $Kp = 10$ and $Ki = 40$ were chosen based on the closed-loop responses shown in Fig. 8. The control objective is to achieve as small as possible settling time subject to stability specification of all four individual control loops.

V. COMPARISON WITH THE TRADITIONAL OPEN-LOOP LOCAL THRESHOLDING

The result of comparison the performance of proposed closed-loop control based local thresholding method with the performances of a traditional adaptive thresholding method is given in Table 2. This traditional method is based on one-dimensional (1D) histogram entropy representing the measure of image information [15]. In contrast to our method, which uses feedback information on quality of ROI in binary image to adjust the local threshold, this method presents a "feedforward action". The 1D entropies of the background and foreground of the ROI in gray level image to be thresholded (in our system edge-detected image) are calculated. Then the threshold which corresponds to the maximum of the sum of background and foreground entropies is determined as the optimal threshold. The abbreviations T and 2DE in Table 2 are used for threshold and 2D entropy of text in individual ROI, respectively.

Table 2

Local Thresholding		ROI1	ROI2	ROI3	ROI4
Open-loop	T	70	50	73	55
	2DE	2.512	2.590	2.635	2.710
Closed-loop	T	38	20	34	26
	2DE	2.280	2.284	2.339	2.156

Obviously the value of 2D entropy of text in each ROI in binary image obtained by proposed closed-loop method is lower then one obtained by conventional open-loop thresholding. Moreover, as a result of PI control action, the achieved values using feedback control are given set points for 2D entropies of each ROI. Consequently, the result of character recognition using proposed method is better than the recognition result using open-loop local thresholding as shown in Fig. 9 for the case of numerical characters 2, 3 and 4.

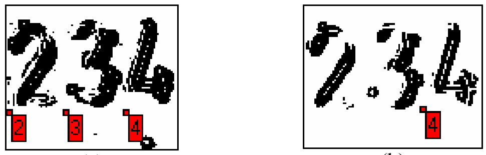


Fig. 9. Character recognition result achieved with the OCR system with closed-loop (a) open-loop (b) thresholding

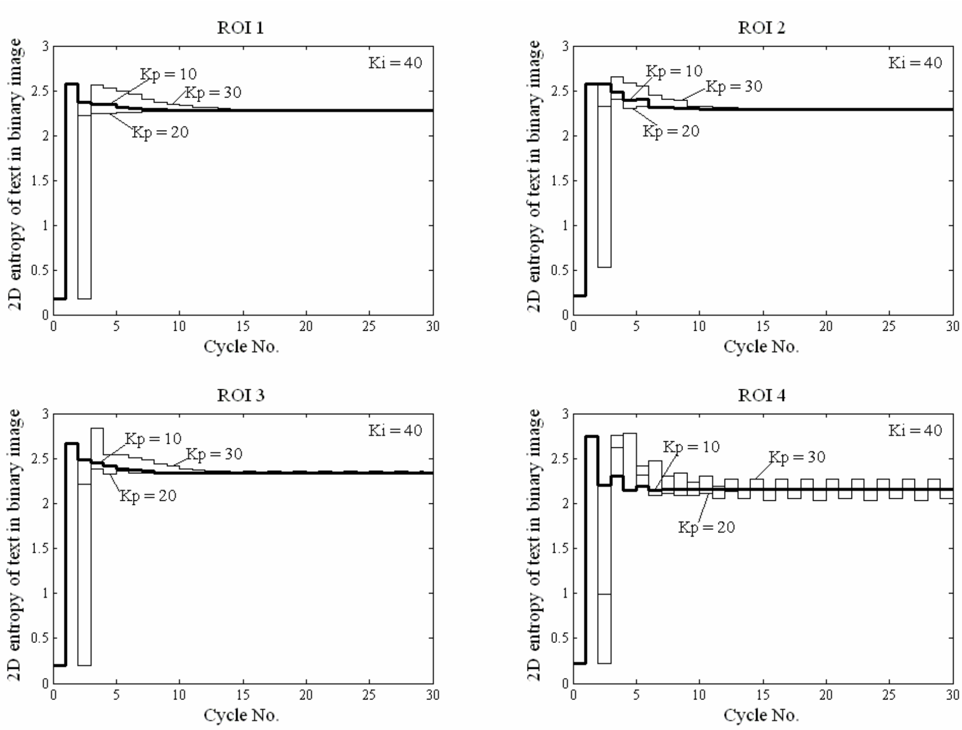


Fig. 8. Closed-loop responses of four ROIs in binary image

VI. CONCLUSIONS

In this paper the idea of inclusion of closed-loop control techniques to improve the robustness and reliability of image processing is discussed. Control of image quality at different processing levels with the emphasis on image segmentation level is considered. The full process of designing the feedback control for solving the problem of character recognition in an unevenly illuminated image is presented. Shown experimental results confirm benefit of the using of feedback information on the quality of binary image to adjust threshold yielding reliable character recognition.

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