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CLOSED-LOOP CONTROL OF SEGMENTED IMAGE QUALITY FOR IMPROVEMENT OF DIGITAL IMAGE PROCESSING

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Abstract. *In this paper the novel idea of including feedback control at the image segmentation level to overcome the problems of traditional digital image processing is presented. The main idea behind this is that the introduced closed-loop drives the current quality of the binary-segmented image to the desired quality, in order to provide the reliable binary image input to the higher processing levels. The conditions that a measure of image quality should satisfy to be used as the controlled variable in a closed-loop are discussed. The two-dimensional entropy of segmented pixels is proposed as a novel measure of the quality of a binary-segmented image that can be used as the feedback variable in the closed-loop control of image segmentation. Besides the input-output selection, both the selection of control structure and feedback control design are considered. The emphasis is on the specific features of image processing that make closed-loop control in this technology different from conventional industrial control. The benefit of feedback control in image processing is illustrated by its successful application to two real-word applications: object recognition in service robotics and corner detection in industrial images for ship welding.*

Key words: *feedback control in image processing, image segmentation, industrial and service robotics image processing applications*

1. INTRODUCTION

Image segmentation, which represents the process of segmenting the image pixels belonging to the objects of interest from the image background, has a central position in the digital image processing chain. As such, image segmentation has a crucial impact on the reliability of the overall system result. Because of this, a large proportion of image processing literature is dedicated to image segmentation [1][2]. However, in spite of the number of published papers, there is still no general method for determining the

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segmentation parameters, which will lead to reliable segmentation results in the presence of the numerous external influences that can arise in real-world applications. In contrast to the majority of robust image segmentation methods, which are based on the determination of optimal segmentation parameters in feedforward actions [3], in this paper the use of feedback information on segmented image quality to adjust the processing parameters is considered. The paper presents the use of the idea of inclusion of feedback structures in image processing to improve its robustness with respect to external influences. This idea is suggested and investigated in detail in [4].

The paper is organized as follows: The principle of the inclusion of feedback control in image processing is given in Section 2. The emphasis is on the choice of the measure of segmented image quality that can be used as feedback variable. The benefit of using the proposed measure for the control of region-based segmentation in a service robotics application is demonstrated in Section 3. Section 4 presents the feedback control of boundary based image segmentation in images from a ship welding scenario.

2. Closed-loop control of image segmentation

In a traditional image processing system, processing levels are arranged sequentially as shown in Fig. 1. This arrangement causes a number of problems. One of the most significant problems is the progress of an uncertainty introduced by a poor quality result of a low-processing level through the image processing sequence, causing unreliability of the higher processing steps regardless of how well designed they are. On the other hand, due to the absence of feedback between the higher and lower levels, the processing at lower levels is performed regardless of the requirements of the subsequent steps. Bearing in mind the central position of segmentation in the processing hierarchy, the inclusion of closed-loops at different low-processing levels aiming at control of segmented image quality is suggested, as shown in Fig. 1. The main idea behind this is to provide higher processing levels, including feature extraction, classification and recognition, with reliable input image data.

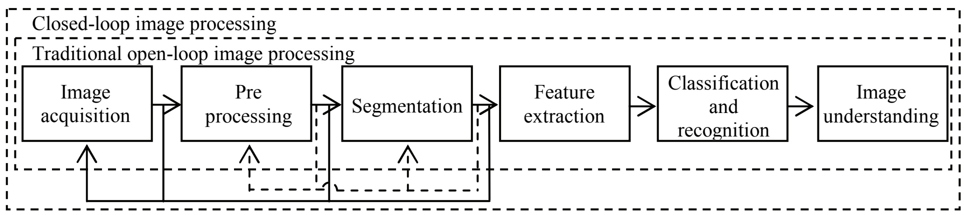


Fig. 1. Block-diagram of standard open-loop and closed-loop digital image processing

There are two types of closed-loops in an image processing system. The first one can be named *image acquisition closed-loop*. In this structure, information from one of the subsequent stages of image processing is used as a feedback signal to control acquisition conditions, as represented with the solid lines in Fig. 1. The second type of closed-loop adjusts the parameters of the processing algorithm at a lower processing level according to the requirements of a subsequent image processing step and so is termed here the *parameter adjustment closed-loop* (the dashed lines in Fig. 1). In contrast to the image acquisition closed-loop, which represents the interaction of the image processing system and its environment, the parameter adjustment closed-loop is fully implemented in software.

2.1. Choice of actuator and controlled variables

The closed-loop control in image processing differs significantly from conventional industrial control, especially concerning the choice of actuator and controlled variables. Following general control design guidelines, the actuator variables should be those that directly influence image characteristics. Hence, for the image acquisition closed-loop these variables can be camera's parameters or the illumination condition while for the parameter adjustment closed-loop they are the parameters of processing algorithms. However, the choice of controlled variable is not a trivial problem. It 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 chosen quality measure has to satisfy input-output controllability conditions and it should be possible to calculate it easily from the image.

The result of a segmentation operation is a binary image consisting of foreground and background pixels. Depending on the implementation, the foreground color is black (0) while background is white (1) or vice versa. The assumption is that the foreground region is of interest in an image to be segmented, corresponding to an object to be recognized, being different from the image background according to a property such as color or texture. Generally, image segmentation algorithms are based either on discontinuity or similarity of pixel values. The segmentation of an image by a method from the first category is based on sharp transitions in pixel values, such as edges in an image. The result of these methods is segmentation of boundaries of the regions of interest and so they are known as *boundary based* segmentation methods. The principal approaches in the second category are based on partitioning an image into regions whose pixel values are similar according to predefined criteria. Because of this, the methods from the second category are known as *region based* segmentation methods. In both cases, a segmented binary image is said to be of good quality if all pixels of region of interest or of region boundary are segmented as foreground pixels. In other words, it is desired to have "unbroken" object regions or object boundaries in the segmented image. Also, it is desired that there are no pixels segmented as belonging to the object region or edges even though they actually do not belong. In other words, it is desired that the segmented image is free of noise. Bearing in mind these requirements for the segmented image quality, it turns out that the number of segmented pixels may be used as a suitable quality measure. Also, a measure of the connectivity of segmented pixels is necessary when assessing segmented image quality. A novel connectivity measure is introduced in [5]. It is the so-called two-dimensional entropy of segmented pixels in a binary image, defined as:

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

where $p_{(0,i)}$ is the relative frequency, that is, the estimate of the probability of occurrence of a pair $(0,i)$ representing the segmented pixel 0 surrounded with i segmented pixels in its

8-pixel neighborhood. It is proved in [4] that the suggested entropy *S* can be considered also as a measure of disorder in an image since *the higher the S, the larger the disorder* (*noise and breaks*) *in a binary image is*.

2.2. Choice of the control structure

There are two types of feedback connections between the chosen actuator and controlled variables in an image processing chain, forming the sequential and cascade control structures respectively.

In the case of the sequential control structure, different closed-loops at sequential levels of the image processing chain are included independently of each other, so that both actuator variables and controlled variables of different control loops are at different processing levels (or sub-levels of the same processing level). Sequential closed-loops are designed so that "lower level" loops contribute to the success of subsequent "higher level" control loops and so to the reliability of the overall vision system. In contrast to the sequential control structure, the cascade structure is characterised by having different closed-loops whose controlled variables are measured at the same image processing level. In this case "inner" control loops provide improvement of the processing result to a certain level while its further improvement is achieved in "outer" loops.

2.3. Feedback control design

Two types of control law specifications are distinguished when including feedback structures at different levels of an image processing chain depending on availability of a so-called *ground truth* image. In the computer vision ground truth is defined as *an ideal description of what should be obtained as the result of processing of a certain image regardless of the processing algorithm.*

The inclusion of a proven error based control algorithm (e.g., PI control law) is proposed in applications where a ground truth is available. The idea behind this approach is to drive the current processing result to the reference one. In applications where the ground truth is not available, the selection of a quality measure, whose minimal or maximal value corresponds to the image of good quality, is suggested for the controlled variable. Then, the control action is realized through an appropriate extremum searching algorithm.

3. CLOSED-LOOP REGION BASED IMAGE SEGMENTATION FOR A SERVICE ROBOT TASK

One of the key requirements of service robotics is robust perception of the environment, aiming at exact 3D localization of objects to be manipulated. For the process of 3D localization based on the robot's vision, the objects of interest firstly have to be reliably recognized in the robots camera image. Service robotic systems such as the system FRIEND II (*Functional Robot arm with frIENdly interface for Disabled people*), which is being developed at the Institute of Automation of the University of Bremen [7], are intended to support the user in daily life activities. Because of this, the object recognition must be robust enough to work effectively in different lighting and background conditions that arise during the day.

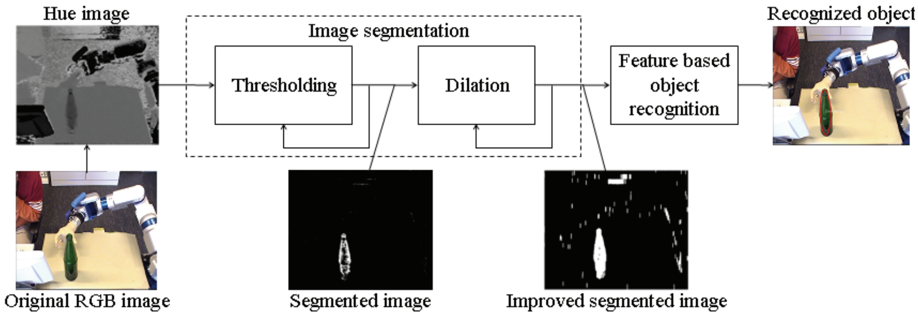


Fig. 2. Robust object recognition based on closed-loop image segmentation in robotic system FRIEND II

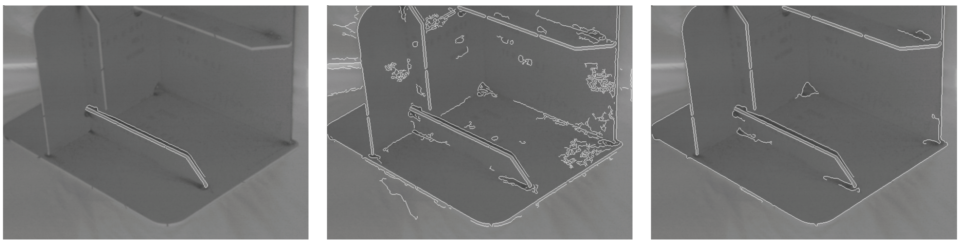
The required robustness of the object recognition, implemented in robotic system FRIEND II, is achieved by inclusion of two sequential closed-loops at the segmentation level as shown in Fig. 2. The first segmentation step, thresholding, is performed on the Hue image containing the pure color information of the original RGB image of the scene from a FRIEND II working scenario. Hence, a pixel from the input Hue image to be segmented is set to the foreground white color in the output segmented image if its pixel value belongs to the thresholding interval determining the particular color class [6]. This operation is highly sensitive to the illumination condition. Due to the pixel color uncertainty arising from changes in the illumination during image acquisition, different threshold values are needed to segment the same object. Manual adjustment of object thresholding interval is quite time-consuming and meaningless during autonomous functioning of the robotic system. Properly tuned proportional and integral gains of implemented discrete PI control structure provide a thresholding closed-loop, which drives the current number of segmented pixel to the reference one.

However, due to reflection during image acquisition all object image pixels are not of the same color even though the object is uniformly colored. Because of that, even the achieved reference number of segmented pixels does not guarantee achievement of the desired quality of segmented image. To overcome this problem, the dilation operation is implemented as the second segmentation step. This operation aims at “filling the gaps” in the segmented object region [6]. Due to the PI control in implemented dilation closed-loop, a dilation parameter is automatically tuned so that the achieved two-dimensional entropy S of segmented pixels is equal to the reference one, providing an object region of well-connected pixels. Reference values for both closed-loops were determined off-line by manual thresholding and dilation of the so-called reference image, which is the image of considered scene taken in artificial “good” illumination condition. In this way, the achieved segmentation result is of good quality independent of the illumination condition (artificial or daily light) during the on-line image acquisition. A well-segmented object region assures reliable extraction of object features that are necessary for correct classification and recognition. Correct recognition is demonstrated by the fact that the bounding ellipse completely surrounds the object as shown in the “Recognized object” image in Fig. 2 for the case of the recognition of green bottle in the “drink serving” scenario of the FRIEND II system.

4. CLOSED-LOOP BOUNDARY BASED IMAGE SEGMENTATION FOR AN INDUSTRIAL APPLICATION

In recent years an extensive investigation into the development of computer vision systems to support the manual welding process has been made. The goal of the system presented in [8] is to provide users with both an improved view on the welding scene and a view augmented with the parameters important for reliable welding. One of the research topics associated with this investigation is the extraction of object feature points such as corners, to provide the user with additional information about the welding task to be done. The nature of the manual welding process raises the need for cameras that are able to cope with the high brightness of the welding arc. The bright welding arc is approximately 10^3 times brighter than the average environmental illumination. Therefore, special high-dynamic range cameras are needed to allow the simultaneous observation of the welding arc and the environment. These cameras map the high dynamic range of brightness to the range of only 256 grey values. As a result, the generated image is of low contrast. Due to the low contrast, those images are very difficult to use for object boundary detection and so for most feature point extraction methods.

The curvature scale space (CSS), which detects corners using the intuitive notion of locating when the contour of an object makes a sharp turn in the image, is a "state-of-the-art" corner detector [9]. However, the success of the CSS is strongly dependent on the quality of the input boundary segmented image, which is obtained by "Canny" edge detection. With default edge detection parameters, the segmentation of a low contrast image of a ship corner, taken in welding preparation phase, is poor, as shown in Fig. 3(a). This under-segmented image is the result of a "too high" threshold used in the thresholding step of the edge detection. However, a "too low" threshold yields an over-segmented image as shown in Fig. 3(b). Neither an under- nor an over-segmented image is a good input to the CSS corner detector. The first one allows detection of only few corners, while the latter one results in detection of too many false positives.



(a) (b) (c)

Fig. 3. Original object image overlaid with the edge-contours detected using "too high" (a), "too low" (b) and optimal (c) threshold

Evidently, it is crucial to define a threshold value that will yield reasonable and efficient segmentation as in Fig. 3(c). The suggested cascade control structure, shown in Fig. 4, aims to do this automatically before the segmentation results are passed to higher level of the CSS system.

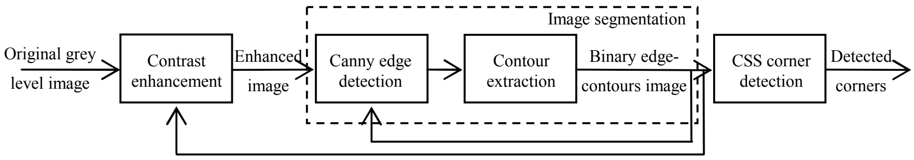


Fig. 4. Cascade control structure for the control of the binary edge-contours image representing the input to the CSS corner detector

In contrast to the application considered in Section 3, here the ground truth reference segmented image is not available. This is because the imaged object is viewed from different positions, which results in different object appearances and consequently in different detected edges. Because of this, the control actions in both control loops of the cascade structure are realized through an optimization procedure. The control objective of the inner closed-loop is to provide a binary segmented image which is free of noise. It is accomplished by changing the threshold of the "Canny" edge detector, so that the measured variable, two-dimensional entropy S of edge segmented pixels, is minimized. The control goal of outer closed-loop is to detect as many true edge-contours as possible. This is achieved by changing the parameter of a preprocessing contrast enhancement operation, so that the contrast of gray level input image is improved, allowing segmentation of more object edges. In this way, the second output variable, the number of segmented edge pixels, is maximized.

In [4] it is demonstrated that this control structure provides an optimal trade-off between the edge length and noise reduction in segmented image, independent of external influences. In this way, the higher levels of the CSS corner detector are provided with reliable input data.

5. Conclusions

This paper presents the benefit of using control techniques in image processing, a new control application field. The usefulness of the proposed measure of segmented image quality, the two-dimensional entropy of segmented pixels, is demonstrated through two real-world applications, an industrial and a service robotics application. These applications are representative of applications with not-available and available so-called ground truth respectively. Correspondingly, the control actions at the segmentation level are realized through an optimization process and classical control techniques respectively. The presented results demonstrate the need for closed-loop image segmentation to provide the reliable input to higher processing levels of the image processing chain and so to fully exploit the advantages of "state-of-the-art" image processing algorithms.

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UPRAVLJANJE KVALITETOM SEGMENTIRANE SLIKE U SISTEMU SA ZATVORENOM POVRATNOM SPREGOM U CILJU POBOLJŠANJA DIGITALNE OBRADE SLIKE

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U ovom radu je prezentovana nova ideja uvodjenja upravljanja sa zatvorenom povratnom spregom na nivou segmentacije slike u cilju prevazilaženja problema tradicionalne digitalne obrade slike u otvorenoj sprezi. Cilj upravljanja u povratnoj sprezi je dostizanje željenog kvaliteta segmentirane slike, tj. obezbedjivanje pouzdanog ulaza u više nivoe sistema obrade slike. U radu se razmatraju uslovi koje mera kvaliteta slike mora da zadovolji da bi se koristila kao upravljana promenljiva u povratnoj sprezi. Dvodimenzionalna entropija segmentiranih piksela se predlaže kao nova mera kvaliteta binarne segmentirane slike koja se može koristiti kao izlazna promenjiva u sistemu automatskog upravljanja segmentacijom slike. Pored selekcije ulaznih i izlaznih veličina, u radu se takodje razmatra i izbor upravljačke strukture kao i projektovanje upravljanja u zatvorenoj povratnoj sprezi. Naglasak je na specifičnostima procesa digitalne obrade slike koje čine sistem upravljanja sa povratnom spregom u ovoj tehnologiji različitim od konvencionalnog industrijskog sistema upravljanja. Korist od upravljanja u povratnoj sprezi u obradi slike se ilustruje prezentacijom dve "real-world" aplikacije: prepoznavanje objekata u servisnoj robotici i detekcija uglova u industrijskim slikama procesa zavarivanja u brodogradnji.

Key words: *upravljanje sa zatvorenom povratnom spregom u digitalnoj obradi slike, segmentacija slike, digitalna obrada slike u servisnoj robotici i u industrijskim aplikacijama*