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Pattern Recognition for Automatic Visual Inspection

by

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PATTERN RECOGNITION FOR AUTOMATIC VISUAL INSPECTION[†]

Abstract

Three major approaches to pattern recognition, (1) template matching, (2) decision-theoretic approach, and (3) structural and syntactic approach, are briefly introduced. The application of these approaches to automatic visual inspection of manufactured products are then reviewed. A more general method for automatic visual inspection of IC chips is then proposed. Several practical examples are included for illustration.

I. Introduction

There are many methods proposed for designing a pattern recognition system. These methods can primarily be grouped into three major approaches; namely, template matching [13], decision-theoretic or discriminant approach [1-9], and syntactic and structural approach [10-12]. From a more general viewpoint, these approaches can be discussed within the same framework in terms of pattern representation and decision-making (based on a given pattern representation). A block diagram of a pattern recognition system, based on this general point of view is given in Figure 1. The subproblem of pattern representation involves primarily the selection of representation. The subproblem of decision-making involves primarily the selection of decision criterion or similarity measure. Other approaches include problem-

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solving models [14], category theory [15] and relation theory [16].

In the template-matching approach, a set of templates or prototypes, one for each pattern class, is stored in the machine. The input pattern with unknown classification is matched or compared with the template of each class, and the classification is based on a preselected matching criterion or similarity measure (e.g., correlation). In other words, if the input pattern matches the template of ith pattern class better than it matches any other templates, then the input pattern is classified as from the ith pattern class. Usually, for the simplicity of the machine, input patterns and the templates are represented in their raw-data form, and the decision-making process is nothing but matching the unknown input to each template.

The template-matching approach has been used in some existing printed-character recognizers and bank-check readers. The disadvantage of this approach is that it is sometimes difficult to select a good template for each pattern class, and to define an appropriate matching criterion. This difficulty is especially remarkable when large variations and distortions are expected in the patterns under study. Recently, the use of flexible template-matching or "rubber mask" techniques has been proposed [17].

II. Decision-Theoretic Approach

In the decision-theoretic approach, a pattern is represented by a set of N features or an N-dimensional feature vector, and the decision-making process is based on a similarity measure which, in turn, is expressed in terms of a distance measure or a discriminant function. In order to take noise and distortions into consideration, statistical and fuzzy-set methods have been proposed [19]. The characterization of each pattern class could be in terms of an N-dimensional class-conditional probability density function or a fuzzy set, and the classification (decision-making) of patterns is then based on a (parametric or nonparametric) statistical decision rule or (fuzzy) membership function. A block diagram of a decision-theoretic pattern recognition system is given in Figure 2.

It should be noted that the template-matching approach could be regarded as a special case of the decision-theoretic approach. In such a case, each pattern is represented by a feature vector, and the decision-making process is based on a simple similarity criterion such as the use of correlation.

Applications of decision-theoretic pattern recognition include character recognition, biomedical data analysis and diagnostic decision-making, remote sensing, target detection and identification, failure analysis and diagnosis of engineering systems, machine parts recognition and inspection in the automation of manufacturing processes, processing of seismic waves modeling of socio-economic systems, and archaeology (classification of ancient objects) [18].

III. Structural and Syntactic Approach

In the structural and syntactic approach, a pattern is often represented as a string, a tree or a graph of pattern primitives and their relations. The decision-making process is in general a syntax analysis or parsing procedure. Special cases include the use of similarity (or distance) measures between two strings, two trees, or two graphs. A block diagram of a structural/syntactic pattern recognition system is given in Figure 3.

Conventional parsing requires an exact match between the unknown input sentence and a sentence generated by the pattern grammar. Such a rigid requirement often limits the applicability of the syntactic approach to noise-free or artificial patterns. Recently, the concept of similarity measure between two sentences and between one sentence and a language has been developed. Parsing can be performed using a selected similarity (a distance measure or a likelihood function), and an exact match becomes unnecessary. Such a parsing procedure is called "error-correcting" parsing.

It should be noted that the template-matching approach could also be regarded as a special case of the syntactic approach. In such a case, each pattern is represented by a string (or tree, or graph) of primitives and the decision-making process is based on a similarity or distance measure between two strings (or two trees, or two graphs).

Applications of syntactic pattern recognition include character recognition, waveform analysis, speech recognition, automatic inspection, fingerprint classification and identification, geological data processing, target recognition, machine part recognition and remote sensing [10].

IV. Automatic Visual Inspection

In this section, we will briefly review published works of automatic visual inspection.* Generally speaking, visual inspection techniques found in today's literature fall into three general categories: (1) pixel-by-pixel comparison of the sensed image of the product to be inspected with some reference pattern (or image), (2) feature inspection method, and (3) generic property verification method. It is not difficult to see that these three inspection methods almost coincide with the three major approaches in pattern recognition described in Section I - Section III.

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*Although the review here is limited to automatic visual inspection, the general methodology presented in this section should be useful also to other inspection tasks.

The idea of the pixel-by-pixel comparison method is very simple and straightforward. Assume that we want to inspect a certain product. First, we generate a defect-free image P of the product. P is called the master image (or reference image) for the inspection task. Such a master image can be generated by the computer or by taking a picture of a defect-free product. P is a two-dimension array of data to be stored in the computer memory. The numerical value of each pixel represents the gray level at that particular pixel. Secondly, the product to be inspected is placed under the sensor to generate a "sensed image" W. Thirdly, the image W is properly aligned to the master image P and then a gray value comparison on the pixel-by-pixel basis is carried out between them. Suppose that W(x,y) is the gray value for the pixel whose coordinate is (x,y) in the image W and P(x,y) is the gray value for the pixel whose coordinate is (x,y) in the image P. Then P(x,y) is subtracted from W(x,y) to get D(x,y). That D(x,y) is zero implies that W is perfect at the pixel (x,y). If the absolute value of D(x,y) exceeds some preset threshold, W is bad at the pixel (x,y).

Mountjoy et al. [26] described an experiment of detecting missing circuit components. The stored master image is subtracted from the sensed image. The difference image resulting from such a subtraction can be used to locate missing components. Today, almost all of commercial machines for automatic or semi-automatic visual inspection work on such a pixel-by-pixel comparison strategy. The Metron circuit board comparator manufactured by the Metron Optics, Inc. in California is built around the comparison of a production line circuit board with a "master" board, identical sections of which are projected on a brightly lighted screen as mirror images of each other. These matching sections are seen magnified and flowing out of a center dividing line on the screen. Components that don't match are errors.

The automatic printed circuit verifier manufactured by Altman Associates, Inc. in Connecticut uses two identically tracking scans. One determines the proper dimensions of the board pattern by examining the artwork. The second scan examines the input board to be inspected. The verifier does not require identicality between the artwork and the input board. Instead, the verifier makes accept/reject decisions based on tolerances and decision criteria stored in the memory of the microcomputer controller.

At Honeywell's Large Information System Division in Phoenix, Arizona, computer technologists are developing micropackaging technology for large scale-integration computer systems. The basic building block of the systems is a "micropac", consisting of a 3 inch x 3 inch substrate coated with 14 layers of dense screen-printed patterns. The inspection system [24] which is manufactured by Photo Digitizing System, Inc. stores a master image of a perfect printed pattern in the computer mass storage. Production units then are scanned and compared with a master image at a rate of 2 million pixels/sec. The digital video inspection system manufactured by Video Tek Inc. in Mountain Lakes, N.J. employs the same comparison technique [23]. The system compares the image of the printed circuit board being inspected with that of an acceptable board, previously stored in memory, and identifies defects on the video display screen for operator action.

The Hitachi Corporation in Japan developed an automatic reticle inspection machine, which is named "ARI-system". A reticle is a photomask of one LSI pellet pattern. The dimension of the reticle is usually ten times as large as the real pellet pattern size. At first, the standard reference pattern for the reticle is generated from the magnetic tape data. And then the actual reticle to be inspected is compared with such a computer generated standard pattern pixel-by-pixel to locate all defects. Hitachi also developed an automatic mask inspection machine for semiconductor photomasks. This machine inspects two photo masks of the same kind simultaneously based on the principle of pixel-by-pixel comparison between the corresponding parts of two masks. The machine consists of a mask carrying XY table, a pair of microscopes of the same magnification with auto-focusing mechanism, and a pair of photo diode array. Initially, those two masks are placed on the XY table and are manually aligned. Any difference between the two is detected and recorded. One implicit assumption of this system is that at any particular pixel, there is at most one of them is defective.

Ito [27] developed a color effect method for the detection of any small defects of LSI mask patterns. Essentially, this is a pixel-by-pixel comparison technique. A master pattern is illuminated by red light, while the pattern to be inspected is illuminated by green light. These two images are projected onto a screen to produce a composite image. Pixels in this composite image which have a color of either black or yellow are defect-free. Any pixel with a red color represents a convex defect. A convex defect means that the master mask is augmented by spurious mask pixels not intended by design. On the other hand, any pixel with a green color represents a concave defect. A concave defect means that part of the master mask is missing. The major advantages of this method are its simplicity and high speed. The comparison process is carried out simultaneously for every pixel in the image. Therefore, it is ideal for applications which demand an instant response. But this method requires the storage of the master image in memory. It may not be practical if the memory resource is limited. Another shortcoming is the inflexibility of inspection criteria. Any inspection criterion that includes more information than just the gray value of a pixel cannot be easily implemented by this method. Throughout this method, each pixel is processed independent of its neighbors. That is to say, contextual information contained in the image has been ignored.

V. Feature Inspection Method

In this method, a storage of the master image P is not needed. Instead, a set of characteristic measurements, called features, are extracted from the master image P and stored as the reference feature vector F(P). As before, the product to be inspected is exposed to the sensor to generate a sensed image W. By taking feature measurements on the image W, we can get the feature vector F(W) of W. Then the feature difference vector D(W) = F(W) - F(P) is obtained by subtracting F(P) from F(W). The vector D(W) is examined with reference to the inspection criteria to detect any existent defect.

Klein and Breeding [30] developed an automatic inspection system for the detection of faults in the bubble memory overlay patterns. The images used are binary images. Each time a small block of the whole image is inspected. Two sets of histograms are obtained from such a block; horizontal and vertical. The ith element of the horizontal histogram represents the number of white cells on row i of the block. Similarly the jth element of the vertical histogram represents the number of white cells on column j of the block. These two histograms are then compared with those of a standard pattern to localize the faults in the block.

Baird [31,32] developed a visual inspection system. The product to be inspected is composed of two components: A Darlington IC chip and a heat sink. Firstly, the relative position of the Darlington IC chip with respect to the heat sink is determined. If the chip is found to be off the edge of the heat sink or too close to the weld cup, a misregistration defect is found. Secondly, the inspection focuses on the integrity of the IC chip.

In other words, broken, cracked, under-sized, fractured and missing chip have to be identified. The feature used here is the contrast across each of the four boundaries of the Darlington IC chip. Contrast is computed as the difference between the average gray value along the chip boundary and the average gray value of the heat sink adjacent to the chip boundary. If the entire boundary of the Darlington IC chip breaks apart, the contrast will fall below some preset threshold. Thereby the system would recognize it as a defective chip.

Jarvin [37] has designed a system for the inspection of Western Electric Series 700 connectors. The connector consists of a slotted "U" shaped contact, preassembled into a two-piece sealant-filled plastic housing. A splice is made inserting the wire into the housing and compressing it to make the contact cut through the wire insulation, and thus to make the connection. The connector is inspected by viewing it from the side using transmitted light. Nine features in terms of gray-level intensities in the contact and sealant areas are used to characterize a connection. Inspection is carried out by an algorithm involving these nine features and thresholds that have been determined to separate the good and the bad parts.

In the feature inspection method, the numerical specification on various features often represents a satisfactory characterization of the product. But when we are dealing with a quite complex product, nice and powerful features can not be found easily or clearly defined. In this case, we need to explore the image deeply to gain the insights. Consequently, a more general and suitable approach to a better characterization of the product is needed. Such a general approach is proposed in Section VII.

VI. Generic Property Verification Method

This method is the commonly called non-reference method and has attracted many researchers in recent years. The most striking characteristic of such a technique is that no comparison of any form between the sensed image W and the master article is needed. Here, the phrase "master article" (or the defect-free product) rather than "master image" is used because the master image may not exist at all. This method relies on its knowledge of localized generic properties only. The knowledge of these generic properties is transformed into a set of generally applicable rules. A small window is moved over the whole sensed image W. At each particular placement of the window only the window area is investigated. If the current window area violates the set of general rules, a defect is found.

A number of researchers have claimed success by making use of this method. Ejiri et al. [28] successfully designed a procedure of detecting defects of printed circuit boards. His observation is that both the conductor patterns and insulator patterns on a printed circuit board are drawn with a round-tip pen and therefore can be regarded as Round Gothic patterns. In other words, there should exist neither a small portion of conductor pattern or insulator pattern, whose radius of curvature is less than the diameter of the round-tip pen, nor a narrow portion of the conductor pattern or the insulator pattern whose width is less than the diameter of the round-tip pen. These are the general rules that detect local defects. Sterling [29] designed an inspection system for printed circuit boards by using the run length approach. Each time, only two consecutive scanlines are examined. He worked out a set of restrictions similar to those observed by Ejiri. Such a set of restrictions are used to detect defects.

A mask pattern inspection system developed by Hitachi Corporation in Japan also uses the third method [33]. Such a system can be applied to the inspection of a mask pattern which contains horizontal, vertical and 45° diagonal line patterns only. A set of templates were developed heuristically. These templates are then moved across the whole image. At each placement of these templates, some defect conditions are checked. A line segment that is neither horizontal nor vertical nor 45° diagonal can be detected and located if those defect conditions are met at some particular placement of the templates.

Another way to represent the set of generic properties is the use of a set of structural or grammar rules. The input pattern is first extracted and processed and then represented by a string. The grammar rules are then applied to the string to detect local defects. Jarvis [36] designs a grammar that characterizes a few defects of printed wiring boards. The conductor boundary pattern of the board under inspection is preprocessed and transformed into a string. Then the string is analyzed to see if any part of it matches the defect grammar. Should it happen, a defect of that type is found.

Mundy and Joynson [39] have developed a system for inspecting industrial parts, such as lamp filaments, screw threads, springs, etc., using the syntactic approach. The system uses a set of (finite-state) grammar rules to analyze the median curves of parts. Straight line approximations are first performed on the median curve of the part under inspection. Straight line segments with different lengths and slopes are used as primitives. The median curve is now represented by a string of primitives and analyzed with respect to the set of grammar rules inferred from a training set of good and defective parts. The approach used is sufficiently flexible to be a candidate approach for inspecting any manufactured part where the median curve is a good representation.

We may be surprised by the fact that a small set of heuristically inferred general rules can be applied in a simple-minded way to solve quite a large class of visual inspection problems. This can be explained in part by the fact that in so many inspection tasks, we are only interested in some position-independent, qualitative properties of the product under inspection. Apparently, such technique can be applied successfully only when the inspection criteria can be transformed into a set of rules that can be applied equally well throughout the whole image. When the inspection criteria demand uneven tolerances at different places, this technique is crippled. For example, some parts of the image are so critical that only a tight tolerance is allowed, while other parts are less critical that the restrictions are generous. This is typical in the inspection of electronic products where different devices demand varying degrees of tolerance.

There are other works which cannot be clearly classified into one of the three approaches. For example, Goto et al. [34] designed a system for the inspection of IC mask patterns, whose operation is not exclusively confined in the third category. A hierarchical detection algorithm is used. At the first level, small defects of local areas are detected. At the second level, local features are combined into macro features to detect macro defects. Heuristically induced geometric rules are applied to the processing of both levels. Some defects such as a line pattern slowly grows thinner until its width goes below a minimum limit can not be detected by the above generic rules. Therefore, a third level processing of feature measurement is added in which the pattern widths and gaps are measured to detect smooth defects.

When it comes to the inspection of a really complex circuit-related product, for example, the inspection of a monolithic integrated circuit, none of the three approaches appears to be powerful enough to solve the problem. Therefore, a more general approach is needed. Such a general approach, which might be considered as a combination of generic property verification and feature inspection methods, is discussed in Section VII.

VII. Automatic Inspection of IC Chips

The proposed automatic visual inspection system for IC chips [40,41] consists of two subsystems: (1) the image segmentation and registration subsystem, and (2) the visual inspection subsystem. The block diagram is shown in Fig. 4. An IC (master) layout pattern is made from n mask subpatterns superimposed on each other, where n depicts the number of planar steps during the IC fabrication process. Since each mask subpattern consists of primarily straight line segments, a natural choice of a primitive is a line segment. In between the mask subpatterns and primitives, we can also introduce module subpatterns. In terms of the syntactic pattern recognition terminology, the pattern P can be decomposed into n subpatterns, each subpattern can again be decomposed into module subpatterns, and then each module subpattern is described by a composition of primitives (line segments).

The purpose of image segmentation is to extract the image of the IC chip from the background. This can often be done by a simple thresholding method. Next the gross registration of the IC chip is achieved by determining the orientation and position of the mask frame of the IC chip. Then the coordinate axes of the IC chip can be aligned with the axes of the inspection machine. Since an IC chip image is in general a multi-layer image, each mask subpattern has to be micro-registered separately and independently. The detailed block diagram of the proposed IC visual inspection system is given in Fig. 5. In Fig. 5, eight types of IC defect are considered. The collection of image filters is called a task-dependent and context-dependent image transformer. Although its particular operation depends on the type of defect under investigation, the proposed image transformation carries out the following three basic functions: (1) focusing, (2) reduction of ambiguity by making use of contextural information, and (3) image coding.

Important features for inspection include (1) the threshold that discriminates aluminum-covered pixels from aluminum-free pixels, (2) the width requirement of an aluminum module subpattern, and (3) the contrast between a mask subpattern and its neighborhood or context. Various thresholds are determined from a training set of IC images and/or design database for these features. The outputs from the eight defect detectors are then summarized by a classifier, which, using simple logical operations, classifies the IC under inspection into three classes: (i) accept, (ii) reject, and (iii) to be reworked. An accepted IC chip is passed on to the final packaging system, which solders the IC chip to the package substrate by the so-called die-bonding process [42-44].

VIII. Concluding Remarks

The purposes of automatic inspection of manufactured products are (1) detection of defects, and (2) verification of performance. Many pattern recognition techniques have already been applied to automatic inspection with successful results. It should be kept in mind that the special characteristics of automatic inspection include: (1) the inspection test must be nondestructive, (2) the inspection process can usually be conducted under a controlled environment (e.g., selection of illumination and sensors), and (3) a stringent performance requirement, such as high speed, accuracy nd reliability, is often required. The characteristic (2) appears to be an advantage in applying pattern recognition methods to automatic inspection. However, characteristics (1) and (3) often result in fairly strong constraints in practical applications. As a matter of fact, the stringent requirement of high speed performance often limits the application of pattern recognition methods to rather simple ones. Most visual inspection tasks are carried out on the basis of simple shape features and/or heuristically inferred structural or design rules. Nevertheless, with the recent progress in special computer architecture (e.g., array processing, pipeline processing and parallel processing) and VLSI technology, it should be possible to apply more sophisticated pattern recognition techniques to more difficult automatic inspection problems.

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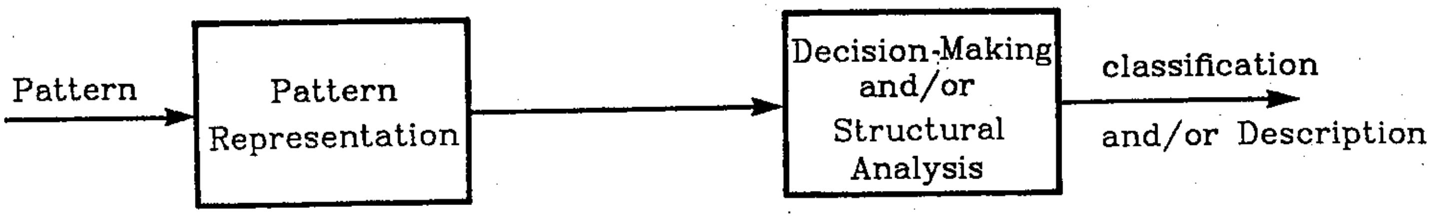

Fig. 1. A general pattern recognition system.

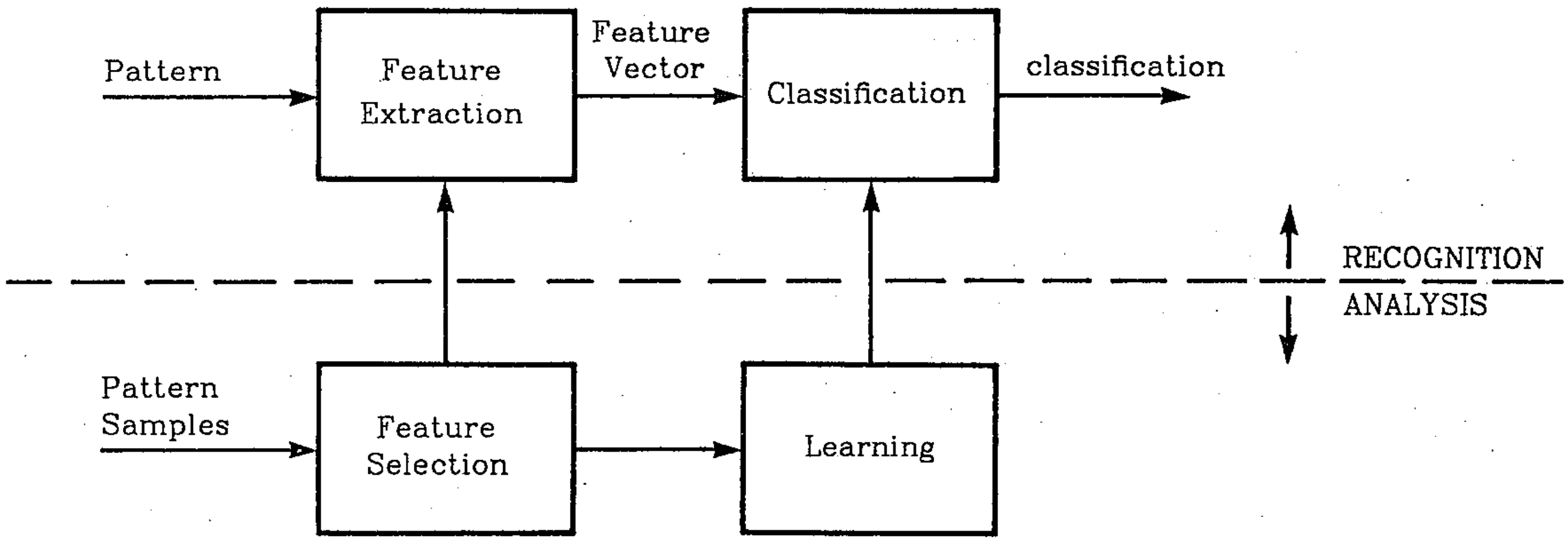

Fig. 2. Block diagram of a decision-theoretical pattern recognition system.

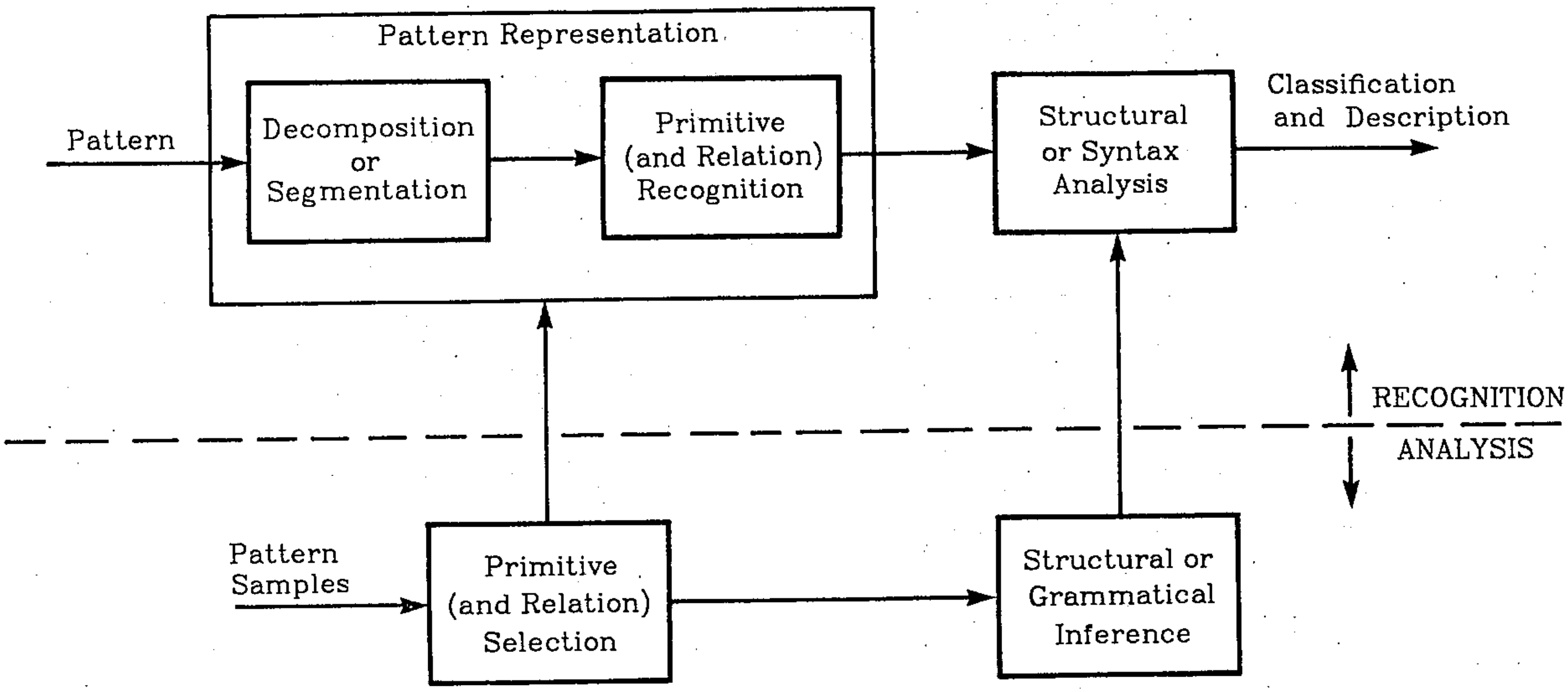

Fig. 3. Block diagram of a structural/syntactic pattern recognition system.

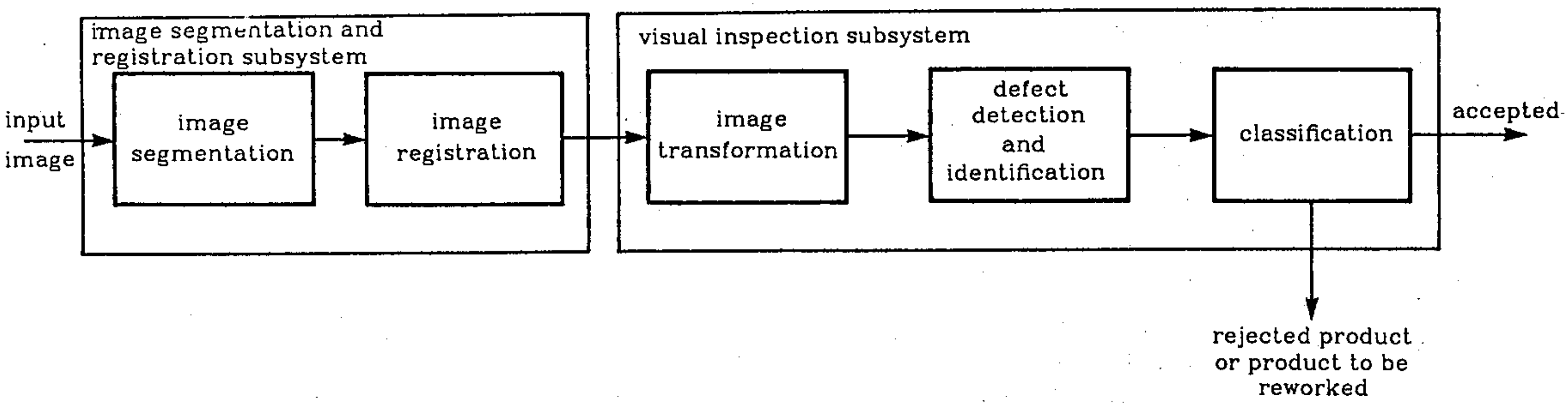

Fig. 4. Block diagram of an automatic visual inspection system.

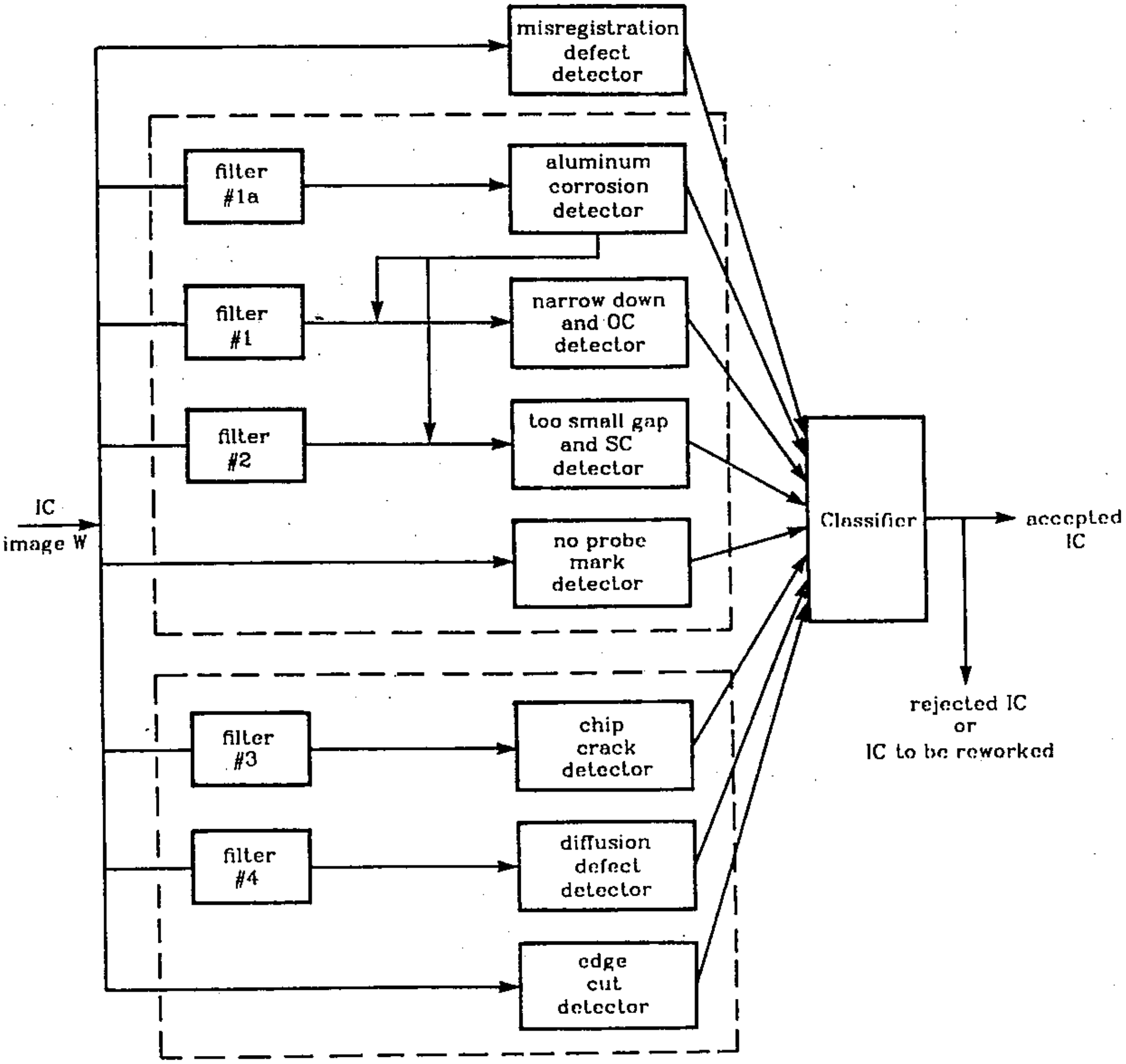

Fig. 5. Block diagram of the proposed IC visual inspection system.