Optical Techniques for Industrial Inspection

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National Research Council of Canada
Industrial Materials Research Institute
Boucherville, Quebec, Canada

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Preface

On-line and unsupervised industrial inspection for quality control and process monitoring is increasingly required in the modern automated factory. Optical techniques are particularly well suited to industrial inspection needs because of their noncontact nature and imaging capabilities. Optical sensors can be used for remote inspection of high temperature products or otherwise inaccessible parts, provided they are in a line-of-sight relation with the sensor. Moreover, the imaging capabilities of optical systems enable the simultaneous collection of large amounts of information and hence the possibility of compensating for variable part position and orientation with respect to the sensor. This is an important requirement in a flexible automation industrial environment.

Electro-optical technology is now mature for operation in hostile industrial environments. One of the main reasons for the growing interest for optical inspection systems in the industrial world is the recent appearance of rugged, reliable and affordable optoelectronic components. The development of such components is mainly a spin-off of the rapid adoption of optical technology in fields such as fiber optic communications and optical disk devices. One example is the laser diode, a coherent solid state source which is extremely compact and surprisingly powerful as compared to the earlier gas laser devices. Such diodes have a lifetime ten times longer than an ordinary tungsten lamp at prices which are rapidly approaching those of inexpensive incoherent light sources. Other important advances in optical technology which are directly relevant to optical inspection requirements are in the fields of optical detectors, compact staring-array video devices and signal processing capabilities.

This book is organized in such a way that optical techniques are introduced as an answer to industrial inspection needs. Rather than describing each technique and its applications separately, the industrial requirements are first outlined in Chapter 1, while Chapter 2 gives an overview of the competitive possible approaches using techniques other than optical. Optical methods are then described in the subsequent chapters, each dealing with a specific industrial inspection field. Comparisons are thus favored between different optical as well as nonoptical methods, and development efforts are justified in terms of the basic industrial needs. In an effort to make each chapter as self-contained as possible, some specific optical techniques relating to different inspection problems are discussed in several chapters.

The book is directed to an audience encompassing optical scientists who are aiming at the industrial inspection sector, practicing engineers in search of suitable sensors for industrial control requirements, as well as students specializing in industrial inspection technology or in electro-optic instrumentation. Chapters 1 and 2 are particularly directed to optical scientists who are not familiar with industrial needs and nonoptical inspection systems, while Chapter 3 reviews modern optical technology for the benefit of engineers having a limited optoelectronics background. As a general rule, only a knowledge of introductory college level optical physics and of general instrumentation is assumed.

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P. Cielo

Contents

Chapter 1

Need and Functions of Industrial Inspection

1.1 Definition and Scope of Inspection Activities in Industry

In the broadest industrial sense, inspection may be defined as the function of determining the conformance of the product to the requirements. Similar expressions which are also used in this context are *quality control, statistical process control, industrial sensing and gaging* or *nondestructive testing.*

In the modern materials processing and manufacturing industry, the main inspection requirements are in the fields of product specification and industrial process monitoring. The term *quality control* refers to the first of these two requirements. Such controls are usually performed on the finished product and are mainly devoted to verifying product quality as it may be assessed by the customer. Visual inspection of the product appearance, color, surface finish and geometrical characteristics are typical examples of controls which are being increasingly performed by means of a quantitative machine inspection approach.

The present trend toward automated production has intensified the need for on-line inspection at each production stage to remove faulty products from the production line before incurring additional product transformation expenses in subsequent manufacturing steps. The detection through a *statistical process control*, of repetitive faults in the product after a given step usually indicates a malfunction of the manufacturing process. On-line inspection tools are desirable to control the automated production process, a function which was carried out by the operator in the nonautomated process. A further step consists of using the information continuously supplied by the inspection sensors to feed the decision making unit of a Computer-Integrated-Manufacturing system. In this case, the sensor acts as the essential portion of a feedback loop which finely modifies the process parameters as soon as minute departures from product specifications are detected. In a Flexible-Manufacturing-Technology environment, the choice of the process to execute relies on sensor information about the workpiece. The term *sensing and gaging* is a general expression which encompasses both quality control and process monitoring activities.

The concept of *testing* refers to the procedure of submitting the product to the function for which it has been designed in order to verify its suitability to this function. For example, an insulated high voltage cable may be submitted to a voltage level higher than the maximum level expected during service or a pressure vessel may be raised to a pressure 50% higher than in the typical in-service operation. Such tests are often too expensive to be performed on 100% of the production. Moreover, a static initial test is usually not sufficient to assure that the product will not fail during the predicted operation life. A pressure vessel may survive a sudden pressure burst to 150% of the operation pressure but may fail after 1,000 pressure cycles not exceeding the normal operation pressure because of cumulative fatigue effects during service. Destructive fatigue tests are thus routinely conducted on products such as nuclear pressure vessels or aircraft structures to evaluate the expected lifetime of such products under normal loading conditions. Safety sensitive structures are automatically withdrawn from service after a fraction of their lifetime in order to avoid catastrophic failures. Destructive test procedures required to obtain statistically significant lifetime predictions are extremely expensive and by definition cannot be applied to 100% of the production. *Nondestructive-testing*, or *-evaluation*, or *-inspection* procedures, are thus widely used both in the production process and during service to collect indirect information on product integrity and suitability. Typical physical properties which may provide such information are thickness and uniformity of structure components and coatings or the presence of surface irregularities and cracks. Optical inspection techniques such as fluorescent-penetrant inspection, holographic pressure testing or thermographic depth-imaging are an expanding subfield of nondestructive testing techniques.

1.2 Human Versus Automated Inspection

Inspection is an integral aspect of manufacturing activity, and human inspection dates back to the stone age craftsman examining his workpiece during carving. Operator-performed manual, and particularly visual, inspection is still by far the most widespread product control activity in the modern production plant. It has been indicated (Geverter, 1982; Miller, 1985) that as much as 90% of all industrial visual inspection activities might be performed by computer vision within the next decade.

Human inspection, as compared to automated inspection, is much simpler and faster to set up, while human versatility and judgement make a strict and detailed specification of the product requirements and tolerances unnecessary. Conversely, inspection machines are not affected by fatigue or task monotony, and they provide reliable decisions based on objective criteria which are not expected to change, as in the case of human inspection, when the inspector changes. Verifying the repetitivity of a given color in a garment manufacturing line may prove a difficult task for the quality control operator, while color quantification is very easily performed by a chromaticity measuring optical system.

The effect of human fatigue and psychological effects in human inspection may be appreciated from a typical rate-of-inspection curve of the kind shown in Figure 1-1 (Kennedy and Andrews, 1977). Such a curve is the result of a series of studies whereby an inspector undertook a 100 percent visual inspection task of the same item at increasing production rates. The fraction of defects escaping detection was plotted versus the production rate. As the chart in Figure 1-1 shows, practically no defects escaped the inspector when the inspection rate was very slow (at a rate smaller than A. As the pace was stepped up, more defects were missed (range B). However, as the rate was further increased, an increase in inspection efficiency could be observed (range C). This is attributed to less inspection monotony at rate C compared to rate B. Only at higher paces (greater than D) did the effect of fatigue produce a deterioration in inspection efficiency.

The effects of human wear and lack of concentration are less pronounced if the inspection is not continuous, such as in *batch inspection* where a relatively small product lot is inspected after the production process or in *patrol inspection* where a quality control officer makes a round surveillance during the production process. *Continuous inspection* is more appropriate to automated procedures. The choice between human or machine inspection is mainly a consequence of the size and repetitiveness of the production line.

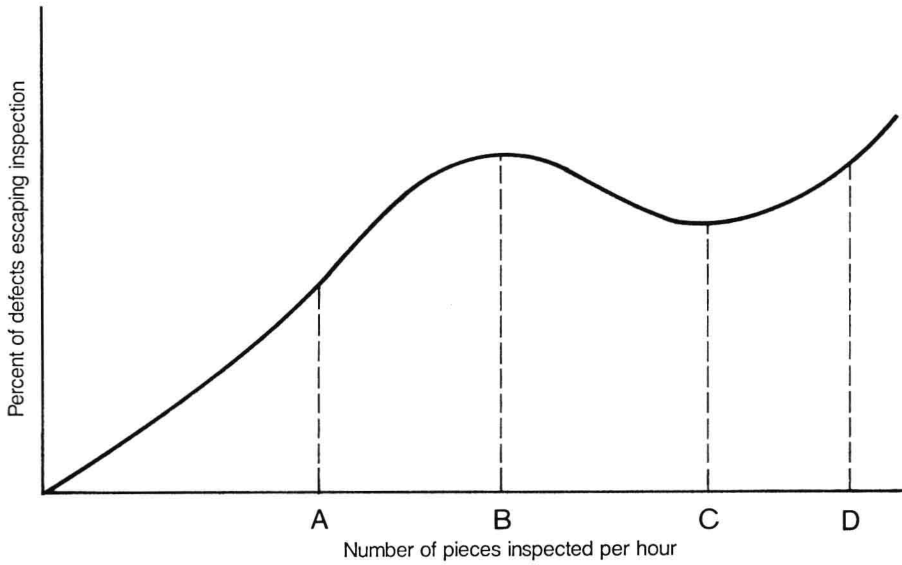

Figure 1-1 The curve shows, for one particular inspector, the relationship between number of pieces inspected per hour and number of defects escaping detection.

In a small shop, the production manager also acts as quality inspector, and for each job the quality criteria depend on the requirements of the specific customer. Usually, human inspection is sufficiently flexible to accommodate the variable requirements of such a production line. At the other extreme are, for instance, the huge automobile plants where thousands of people work on three shifts. Automated inspection is much more suitable to such processes in order to assure reliable and constant quality criteria for all the products at the different production stages. Capital investment and employee retraining capabilities are also much more favorable in such large production units (Batchelor et al., 1985, Section 2.3).

Most inspection procedures are neither totally manual nor completely automated. The human inspector often relies on gaging instruments or on defect enhancing image processing systems to facilitate decision-making activites. On the other hand, highly automated inspection systems often require operator intervention to judge whether a product which does not meet specifications can be fixed or recycled or whether an alarm signal along the production line indicates a problem sufficiently serious to suspend the process. A trend toward increased automation in the quality control and process monitoring fields is, however, clearly discernible in the modern industrial plants.

1.3 Economic Factors

Inspection tasks constitute a sizeable fraction of production costs. It has recently been estimated (Miller, 1985) that inspection activities are performed by 10% of the work force. Optical instrumentation represents a major component of the industrial inspection hardware. A recent report predicts an annual growth as high as 25% in the U.S. market for electro-optical inspection systems, rising from $900 million in 1984 to $3.7 billion by 1990 (*Sensor Review*, July 1986, p. 120).

Quality assurance activities are either compulsory or voluntary. Examples of the first are verification and testing procedures imposed by government regulations on health and safety or export quality controls. Legal requirements may result in substantial inspection costs for safety sensitive products. Quality control as a whole accounts for as much as 60% of the cost of an airplane (Papadakis, 1983).

Except for compulsory procedures, all other inspection activities are based on economic considerations. Product quality is not an objective per se, but must be justified in terms of an improvement in the present or projected profit position of the company.

1.3.1 *Quality and Income*

Product quality may affect income because of its effects on sales and prices as well as the company's reputation in the market.

Quality and Share of the Market

Once a product is actively on the market, it attains a "share of the market," i.e., a proportion of all sales by all manufacturers for that type of product. The measurement and analysis of consumer preference patterns and the implementation of the appropriate product features to suit such patterns are essential tools available to the company to improve its market share position.

The willingness of the customer to respond to product quality strongly depends on the buyer's capability and motivation to assess the product. As far as industrial products are concerned, such an assessment is performed more on technological performance than on sensory qualities. Product quality features such as fitness, integrity, functionality and durability are high on the list for industrial customers, provided they are made aware of such characteristics.

Products sold to end users in the consumer market are screened on different terms. The consumer is often more influenced by marketing skills including attractiveness of the package and appeal of prior advertisement or the manufacturer's reputation than the intrinsic quality of the product. Figure 1-2 illustrates such behavior, showing the results of a survey on 41 products sold on supermarket shelves (Juran et al., 1979). The horizontal scale shows consumer preference over the leading competitor product as determined by a statistically sound preference testing poll. The vertical scale shows the market share versus the leading competitor, considering the two as constituting 100%. In contrast to the vacant areas on the horizontal scale of consumer preference, the vertical scale of market share has data along the entire spectrum. One product (marked A on Figure 1-2) lies squarely on the 50% consumer preference line, implying that the product quality is very similar to the competitor. Yet this product has only 10% of the market share, compared to 90% for the competitor, the reason being that the competing company pioneered this particular product, thus acquiring a strong initial share of the market which is retained thereafter through good promotion.

The relation of product quality to customer preference must be based on objective marketing data rather than on manufacturer assumptions. In the

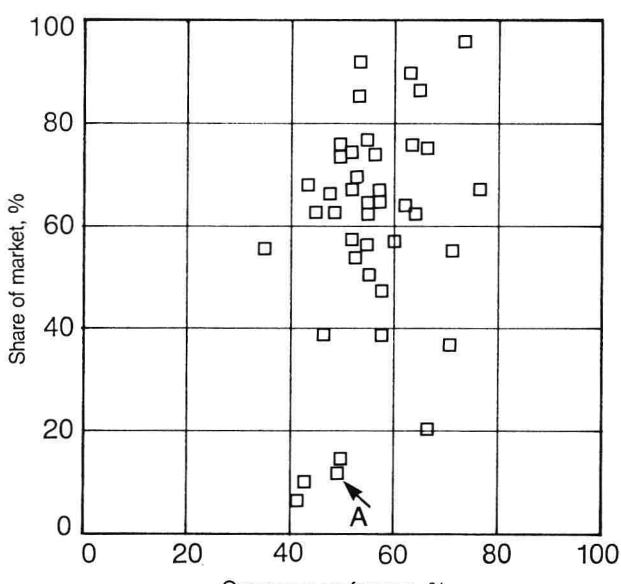

Figure 1-2 Consumer preference versus share of market.