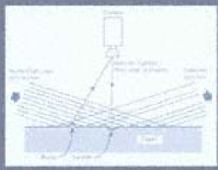
UNDERSTANDING AND APPLYING MACHINE VISION

SECOND EDITION, REVISED AND EXPANDED



NELLO ZUECH

Understanding and Applying Machine Vision

MANUFACTURING ENGINEERING AND MATERIALS PROCESSING

A Series of Reference Books and Textbooks

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Preface

This book was written to inform prospective end users of machine vision technology, not designers of such systems. It provides the reader with sufficient background to separate machine vision promises from machine vision reality and to make intelligent decisions regarding machine vision applications.

The emphasis of the text is on understanding machine vision as it relates to potential applications and, conversely, understanding an application as it relates to machine vision. The book is designed to serve as a translator so a potential buyer can convey his requirements comprehensively. It will also provide the prospective buyer with basic understanding of the underlying technology embedded in machine vision systems.

The first chapter sets the tone for the book. It emphasizes that machine vision is a data collector, and thus the value of a machine vision system is in the data itself. Chapter 2 delves into the history of machine vision. Chapters 3 and 4 discuss principles in lighting, optics and cameras. The application engineering surrounding these elements of a machine vision system typically account for 50% of the design effort. Chapter 5 reviews the underlying image processing and analysis principles associated with machine vision. Chapters 6 and 7 discuss three-dimensional and color machine vision techniques.

The rest of the book is designed to provide a roadmap for successfully pursuing a machine vision application. Chapter 8 describes the various players that constitute the machine vision industry. Chapter 9 provides a means to perform a "back-of-the-envelope" estimate to determine the feasibility of a specific application. Chapter 10 reviews specific tactics to employ as one proceeds to deploy machine vision within a factory. Following the procedures given here will increase the probability of a successful installation.

NELLO ZUECH

Contents

1— Machine Vision: A Data Acquisition System

Machine vision is not an end unto itself! It represents a piece of the manufacturing/quality control universe. That universe is driven by data related to the manufacturing process. That data is of paramount importance to upper management as it relates directly to bottom-line results. For competitiveness factors, top management can not delegate responsibility for quality control. Quality assurance must be built in - a function totally integrated into the whole of the design and manufacturing process. The computer is the means to realize this integration.

Sophisticated manufacturing systems require automated inspection and test methods to guarantee quality. Methods are available today, such as machine vision, that can be applied in all manufacturing processes: incoming receiving, forming, assembly, and warehousing and shipping. However, hardware alone should not be the main consideration. The data from such machine vision systems is the foundation for computer integrated manufacturing. It ties all of the resources of a company together - people, equipment and facilities.

It is the manufacturing data that impact quality, not quality data that impact manufacturing. The vast amount of manufacturing data requires examination of quality control beyond the traditional aspects of piece part inspection, into areas such as design, process planning, and production processes.

The quality of the manufacturing data is important. For it to have an impact on manufacturing, it must be timely as well as accurate. Machine vision systems when properly implemented can automate the data capture and can in a timely manner be instrumental in process control. By recording this data automatically from vision systems, laser micrometers, tool probes and machine controllers, input errors are significantly reduced and human interaction minimized.

Where data is treated as the integrator, the interdepartmental database is fed and used by all departments. Engineering loads drawing records. Purchasing orders and receives material through exercise of the same database which finance also uses to pay suppliers. Quality approves suppliers and stores results of incoming inspection and tests on these files. The materials function stocks and distributes parts and manufacturing schedules and controls the product flow. Test procedures stored drive the computer-aided test stations and monitor the production process.

The benefits of such an "holistic" manufacturing/quality assurance data management system include:

Increased productivity:

Reduced direct labor
Reduced indirect labor
Reduced burden rate
Increased equipment utilization
Increased flexibility
Reduced inventory
Reduced scrap
Reduced lead times
Reduced set-up times
Optimum balance of production
Reduced material handling cost and damage

Predictability of quality
Reduction of errors due to:

Operator judgement
Operator fatigue
Operator inattentiveness
Operator oversight

Increased level of customer satisfaction

Holistic manufacturing/quality assurance data management involves the collection (when and where) and analysis (how) of data that conveys results of the manufacturing process to upper management as part of a factory-wide information system. It merges the business applications of existing data processing with this new function.

It requires a partnership of technologies to maximize the production process to ensure efficient manufacturing of finished goods from an energy, raw material, and economic perspective. It implies a unified system architecture and information center software and database built together. This integrated manufacturing, design and business functions computer based system would permit access to data where needed as the manufacturing process moves from raw material to finished product.

Today such a data driven system is possible. By placing terminals, OCR readers, bar code readers (1D and/or 2D) and machine vision systems strategically throughout a facility it becomes virtually paperless. For example, at incoming receiving upon receipt of material, receiving personnel can query the purchasing file for open purchase order validation, item identification and quality requirements. Information required by finance on all material receipts is also captured and automatically directed to the accounts payable system.

The material can then flow to the mechanical and/or electrical inspection area where automatic test equipment, vision systems, etc. can perform inspection and automatically record results. Where such equipment is unavailable, inspection results can be entered via a data terreinal by the inspector. Such terminals should be user-friendly. That is, designed with tailored keys for the specific functions of the data entry operation.

Actual implementation of such a data driven system will look different for different industries and even within the industry different companies will have different requirements because of their business bias. For example, a manufacturer of an assembled product who adds value with each step of the process might collect the following data:

Receiving inspection:

a. Total quantity received by part number

b. Quantity on the floor for inspection

c. Quantity forwarded to production stock

d. Calculation of yield

Inventory with audit (reconciliation) capability:

a. Ability to adjust, e.g., addition of rework

b. FIFO/LIFO

c. Part traceability provisions

d. Special parts

Production:

a. Record beginning/end of an operation

b. Ability to handle exceptions - slow moving or lost parts

c. Ability to handle rework

d. Ability to handle expedite provisions

e. Provide work in process by part number, operation

f. Provide process yield data by:

Part number
Process
Machine

g. Current status reporting by:

Part number
Shop order number
Program operation
Rejection

h. Activity history of shop order in process including rework

i. Shop orders awaiting kitting

j. Shop orders held up because of component shortages

k. History file for last "X" months

l. Disc and terminal utilization

Quality:

Provide hard copy statistical reporting data (pie charts, bar diagrams, histograms, etc.)

Data input devices:

a. OCR

b. Bar code readers (1D and 2D)

c. Keyboards

d. Test equipment

e. Machine vision systems

Personnel:

a. Quality control inspectors

b. Production operators

c. Test technicians

With appropriate sensor technology, the results include unattended machining centers. Machine mounted probes, for example, can be used to set up work, part-alignment, and a variety of in-process gaging operations. Microprocessor-based adaptive control techniques are currently available which can provide data such as:

Tool wear
Tool wear rate greater or less than desired
Work piece hardness different from specification
Time spent
Percentage of milling vs. drilling time, etc.

Quality assurance can now use CAD/CAM systems for many purposes; for example, to prove numerical control machine programs, and provide inspection points for parts and tools.

After the first part is machined, inspection can be performed on an off-line machine vision system analogous to a coordinate measurement machine using

CAD developed data points. This verifies the NC program contains the correct geometry and can make the conforming part. At this point QA buys off the program software. While the program is a fixed entity and inspection of additional parts fabricated for shape conformance is not needed, inspection is required for elements subject to variables: machine controller malfunction, cutter size, wrong cutter, workmanship, improper part loading, omitted sequences and conventional machining operations. This may necessitate sample inspection of certain properties-dimensions, for example, and a 100% inspection for cosmetic properties - tool-chatter marks, for example.

The CAD/CAM system can be used to prepare the inspection instructions. Where automatic inspection is not possible, a terminal at the inspection station displays the view the inspector sees along with pertinent details. On the other hand, it may be possible in some instances to download those same details to a machine vision system for automatic conformance verification. CAD systems can also include details about the fixturing requirements at the inspection station. This level of automation eliminates the need for special vellum overlays and optical comparator charts. The machine vision's vellum or chart is internally generated as a referenced image in the computer memory.

While dimensional checks on smaller parts can be performed by fixturing parts on an X-Y table that moves features to be examined under the television camera, using a robot to move the camera to the features to be inspected or measured can similarly inspect larger objects. Again, these details can be delivered directly from CAD data.

Analysis programs for quality monitoring can include:

1. Histogram which provides a graphic display of data distribution. Algorithms generally included automatically test the data set for distribution, including skewness, kurtosis and normality.

2. Sequential plots, which analyze trends to tell, for example, when machine adjustments are required.

3. Feature analysis to determine how part data compares with tolerance boundaries.

4. Elementary statistics programs to help analyze data of workpiece characteristics-mean, standard deviation, etc.

5. X-bar and R control chart programs to analyze the data by plotting information about the averages and ranges of sequences of small samples taken from the data source.

A computer-aided quality system can eliminate paperwork, eliminate inspection bottlenecks and expedite manufacturing batch flow. The quality function is the driver that merges and integrates manufacturing into the factory of the future.

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2— Machine Vision: Historical Perspective

The concepts for machine vision are understood to have been evident as far back as the 1930's. A company - Electronic Sorting Machines (then located in New Jersey) - was offering food sorters based on using specific filters and photomultipliers as detectors. This company still exists today as ESM and is in Houston, TX. Satake, a Japanese company, has acquired them. To this day they still offer food sorters based on extensions of the same principles.

In the 1940's the United States was still using returnable/refillable bottles. RCA, Camden operation, designed and built an empty bottle inspection system to address the concern that the bottles be clean before being refilled. Again, the system used clever optics and a photomultiplier tube as the detector. As with the early food sorters, this technology was all analog-based. It is noted that over 3000 of these systems were installed. It is also understood that they adapted the basic principles to "check" detection - inspecting for cracks on the bottle lips.

The field of machine vision has evolved along with other evolutions involving the use of computers in manufacturing. The earliest related patents were issued in the early 1950s and concerned optical character recognition. Pattern recognition and analysis received a big push due to the research sponsored by the National Institute of Health (NIH) for chromosome analysis and various types of diagnostics based on blood and tissues associated with automatic tissue culture or petri culture analysis. These typically involved counting of cells designated by a common optical density.

The military supported a great deal of research and development (R&D) to provide operator assistance in interpreting and/or automating the interpretation of surveillance photos as well as for automated target recognition and tracking. In the late 1960's computer-vision-related research was being funded by the military at the Al Labs of MIT and Stanford University. NASA and the U.S. Geological Survey also supported R&D in this field. In an attempt to emulate the eye's performance, the military and the NIH have supported much research to provide an understanding of how the eye operates.

Along with the technology, government research support has spawned a cadre of people trained in computer-based vision. The National Science Foundation (NSF), the National Institute of Standards and Technology (formerly the Bureau of Standards), and the military have actually supported R&D specifically in the field of machine vision.

In 1962, optical character recognition was demonstrated using TV-based apparatus and computers. In the 1960's much R&D was being conducted driven by military objectives to enhance images for photoreconnaissance interpretation. Work also began during this time in imaging-related research supported by health/diagnostic objectives.

In the early 1960's IT&T delivered an image-dissector-based (an early TV camera) system to inspect reflectors, etc. to General Motors. At this same time, Proctor & Gamble was also experimenting with concepts to inspect Pampers.

In 1964, Jerome Lemelson was awarded a patent application for a generic concept: to capture electromagnetic radiation using a scanner device, digitize the signal and use a computer to compare the results to a reference stored in memory. A subsequent patent was awarded in 1971 with a similar specification and new claims. In the late 1970's he began filing more patents with essentially the same specification and new claims maintaining continuance to the original patent filing. This resulted in over a dozen machine-vision-related patents.

In 1965, a doctor intent on applying the technique to Pap smear diagnostics developed the concepts behind Object Recognition Systems' pattern recognition system. During this time there was other activity along these lines.

In 1965, Colorado Video was formed, providing a unit to digitize video images. It basically, digitized one pixel per line for each scan. In other words, it required 500 scans to digitize an entire image. In 1970, driven by military objectives, GE demonstrated a 32 × 32 pixel CID camera and Bell Labs developed the concept of charge coupling, and created the CCD (charge coupled device). In 1971, Reticon developed its first sold state sensor.

In 1969, driven by a NASA project, EMR Photoelectric, a Schlumberger company, developed the Optical Data Digitizer. This was an all-digital camera, taking signals, from a PDP-11 to expose, scan and digitize an image. It had features such as selective integration so one could restrict digitizing to just the areas of interest. Early versions of the camera were sold for: TV interferometric-based measurements, optical computing applications, TV-based spectrometers, X-Ray digitizing, and motion analysis for prosthesis evaluation/biomechanics. By 1974 the system had been used to read characters on rifles and inspect fuses. The OCR system actually used a 256 × 256 × 4- bit frame grabber.

In the late 1960s, minicomputer-based image analysis equipment became available for biological and metallurgical pattern recognition examinations. In general, commercially available products had limited performance envelopes and were very expensive. In the early 1970s, the NSF began to support applied research focused on specific advanced manufacturing technology issues. Several of these included projects on machine vision. In virtual synchronization with the flow of the results of these research efforts, microcomputer performance was improving, and costs were decreasing. Similarly, advances were being made in fiber optics, lasers, and solid-state cameras.

By the early 1970's several companies had been formed to commercialize TV-based inspection systems. For the most part these commercialized products were analog-based. Autogage was a company started by Jay Harvey in Connecticut. Ball Corporation and Emhart introduced systems to inspect the sidewall of bottles. Intec was established in 1971 offering a flying spot scanner approach to inspecting products produced in web form.

In 1971, Solid Photography (now Robot Vision Systems Inc.) was established to commercialize 3D techniques of capturing data from a person to be the basis of creating a bust of the person. The Navy funded research to extend the techniques to inspecting ship propellers. Around this same time, Diffracto was established in Canada to commercialize 3D sensing techniques.

By the mid-1970s, exploratory steps were being taken to apply the technology in manufacturing. Several companies began to offer products that resembled what now appear to be machine vision systems. Virtually every installation had a significant custom content so that the system was really dedicated to performing one task and one task only - controlling the quality of French fries, for example (Figure 2.1).

Some systems also became available that performed tasks with potential for widespread adoption: Pattern recognition systems (Figure 2.2) that automate the wire-bonding process in the manufacture of semiconductor circuits is one such example. Computer-based electro-optical products also entered the marketplace to automatically inspect web products (Figure 2.3), silicon wafers, gage diameters (Figure 2.4), and so on. Toward the end of the 1970s, products became available to perform off-line dimensional measurements essentially automating optical comparator and coordinate measuring-machine-type products (Figure 2.5).

By 1973, several companies had commercialized solid-state cameras. Until this development, all the systems that were based on conventional analog vidicon cameras suffered from the need to continuously "tweak" them to compensate for drift that was generally unpredictable. Fairchild introduced their first commercial

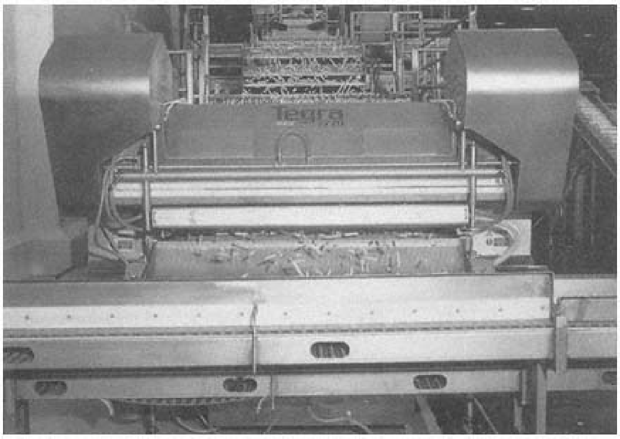

Figure 2.1
Key technology system designed to detect blemishes in french fries as well as other vegetables.

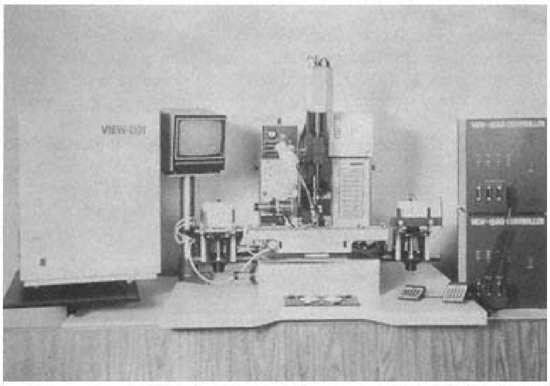

Figure 2.2
Early View Engineering wire-bonding pattern recognition system shown on Kulicke and Soffa wire bonder.

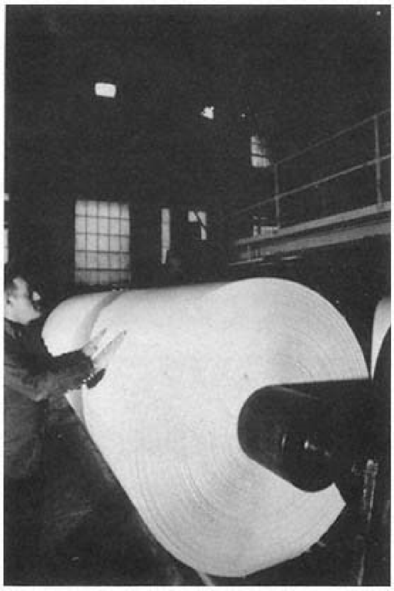

Figure 2.3
Honeywell Measurex scanner verifying the integrity of paper

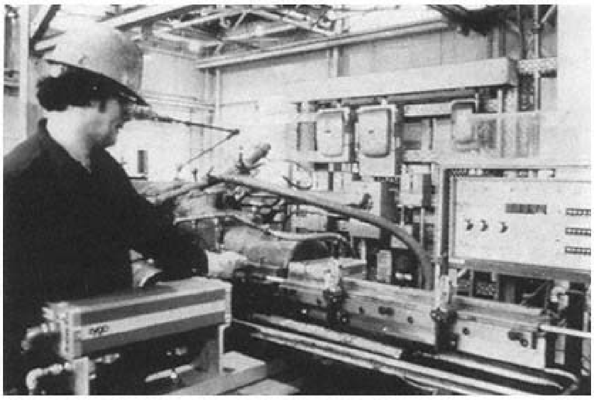

Figure 2.4
Early laser gauging system from Z-Mike (formerly Zygo and now part of LaserMike) used to monitor the results of a grinding process.

Figure 2.5
Version of an off-line dimensional measuring system "Voyager" offered by GSI Lumonics.

CCD sensor; a 500 × 1 linear array ($4000). GE sold its first 32 × 32 pixel CID for $6500. Reticon also introduced 32 × 32 pixel and 50 × 50 pixel cameras. In 1973 Reticon also introduced their 64 Serial Analog Memory and the "SAD m100" for processing image data. They also established a system integrator group.

Two other events cited in 1973 were: GM simulated automobile wheel mounting using vision-guided robotics and ORS introduced a microprocessorbased pattern recognition system based on the 8080 microprocessor. The development of the microprocessor and the development of solid state cameras are what really made the applications of machine vision possible and cost effective.

Around 1973, the National Science Foundation began funding research in machine vision at the University of Rhode Island, Stanford Research Institute and Carnegie Mellon. These three schools all formed industrial affiliate groups as an advisory panel and a means of effecting technology transfer. This led to a number of pioneering demonstration projects related to manufacturing applications. For example, the University of Rhode Island demonstrated a vision-guided bin-picking robot.

Also in the early 1970's research in the field of computer Vision was initiated at many other universities including: University of Missouri, Columbia, Case Western Reserve, several University of California schools, University of Maryland, and University of Michigan.

In 1974, GE introduced a 100 × 100 pixel CID camera for $6500 and later in the year a 244 × 128 version also for $6500. By 1976 they had cut the price to $2800.

In 1975, EMR introduced a TV-based off-line dimension-measuring system. It used a PDP-8 computer and essentially the principles of their Optical Data Digitizer. Shortly after, View Engineering also introduced their system.

In 1976, the following are understood to have occurred: GM first published work on its automatic IC chip inspection system; Fairchild introduced the 1024 × 1 linear array; Reticon introduced its CCD transfer device technology.

In 1977: Quantex introduced the first real-time image processor in a single box; GE introduced their first commercial vision inspection system for sale; SRI introduced a vision module - a laboratory system with camera, analog preprocessor and DEC computer intended for prototyping applications; ORS systems were available for sale; Hughes researchers demonstrated a real-time 3 × 3 Sobel (edge segmenting) operator using a CCD chip for storage and outboard hardware for processing. This development pioneered dedicated hardware and eventually application-specific integrated circuits to speed up software image processing functions.

In 1977, Leon Chassen received a patent applying the principles of structured light to log profiling as the scanner input to an optimization program to increase the yield cut from a log. Shortly thereafter he established Applied Scanning to commercialize the technique.

By 1978, ORS had established a relationship with Hajime in Japan that led to the commercialization of the technology there. In 1978 Octek, another early machine vision company, was founded. By the late 1970s companies, such as Imanco in the UK and Bausch & Lomb in the States, had introduced TV-based computer workstations for metallographic analysis as well as microscopic biomedical analysis.

In 1979, View commercialized pattern recognition techniques out of Hughes for alignment applications for wire bonders and other production equipment for the semiconductor industry. Around this time, KLA was also formed and announced the development of a photomask inspection system. By the early 1980s, Texas Instruments had an in-house group developing machine vision solutions for their own manufacturing requirements. These included pattern-recognition systems for alignment, wafer inspection, and even an off-line TV-based dimensional measuring system.

In 1980, Machine Intelligence Corporation (MIC) was formed to commercialize the SRI machine vision technology. In 1981, Cognex was formed and introduced their first product performing a binary correlation running on a DEC LSI 11/23. Also in 1981, MIC introduced their VS-110, a system intended to perform high speed inspection on precisely indexed parts, by referencing the part's image to a master image stored in memory. The first industrial application of binary thresholded template matching was aimed at highly registered and controlled parts in the electronic industry.

In 1981, Perceptron was formed by principals that came out of General Motors. Also in 1981, Machine Vision International (originally called Cyto Systems) was formed to commercialize the parallel-pipeline cytocomputer coming out of the Environmental Research Institute of Michigan (ERIM) and morphological principles out of University of Michigan and the Ecole des Mines in France. In 1982, Applied Intelligent Systems, Inc. was founded by another group coming out of ERIM to commercialize another version of their developments.

In 1983, Itran shipped their first factory-oriented system to AC spark plugs to perform speedometer calibration. Their system used normalized gray scale correlation for the "find" or locator function. By this time, the industry also witnessed the beginning of the establishment of an infrastructure to support the application of machine vision. Merchant system integrators began to emerge as well as independent consultants. Around this time, GM announced the conclusion of their inhouse analysis that suggested that they alone would require 44,000 machine vision systems.

In 1984, Allen Bradley, acquired the French company Robotronics and became a machine vision supplier.

By 1984, the Machine Vision Association (MVA) was spun out of Robotics International, a professional interest group within the Society of Manufacturing Engineering. Also in 1984, the Robotics Industries Association spawned the Automated Vision Association, a trade association for the machine vision industry.

It has since been renamed the Automated Imaging Association. The term "machine vision" was defined by this group and became the accepted designation to describe the technology. Also, around this time, GM took a 20% position in four machine vision companies: Applied Intelligent Systems, Inc. (for cosmetic inspection applications), View Engineering (for metrology), Robot Vision Systems Inc. (for 3D robot guidance systems) and Diffracto (for 3D systems to measure gap and flushness on assemblies). (They have since disengaged themselves from these companies.)

By this time, one could say that the machine vision industry was well on its way to evolving into a mature industry. With advances in microprocessor technology and solid state cameras and the cost declining of these basic components, things were in place for the industry to grow. Some other noteworthy events:

1984 - NCR and Martin Marietta introduce the GAPP, a single chip systolic array for use in parallel processing for pattern and target recognition.

1985 - VIDEK, a Kodak subsidiary at the time (now Danfoss-Videk), shipped its first unit with dedicated hardware boards to perform edge segmentation, histogramming and matrix convolutions. EG&G introduced a strobe specifically for machine vision - high speed and power.

1987 - Hitachi introduces the IP series using the first dedicated image processing VLSI chip.

1988 - Cognex introduced their VC-1, the first VLSI chip dedicated to image analysis for machine vision. It performs measurements such as blob locations, normalized correlation, feature vectors, image projection at any angle, spatial averaging and histograms.

1988 - Videk introduced the Megaplus camera - 1024 × 1024 resolution.1988 - Sharp introduces 3" × 3" complete image processing function "core board."

1988 - LSI Logic introduces the RGB - HSI converter CMOS chip. It was first applied to color-based machine vision/image processing boards by Data Translation. In 1988, Imaging Technology, Inc. introduced their RTP-150 using LSI Logic's real time Sobel processor and Rank Value Filter chips.

1989 - LSI Logic introduces a contour tracing chip and Plessey Semiconductors introduced ASICs to perform 2D convolutions at 10 MHz rates.

1991 - Dickerson Vision Technologies is one of the first to offer a "smart camera" - a camera with embedded microprocessor that results in a general purpose machine vision flavor

1992 - Cognex introduces the VC-2, a complement to the VC-1.1994 - Cognex introduces the VC-3, an improved VC-1 with higher throughput. They also introduced their Checkpoint system.

1994 - Itran and Automatix merged to form Acuity Imaging.

1995 - Acuity Imaging became a subsidiary of RVSI; Cognex acquired Acumen. Some suggested that consolidation began.

1995 - KLA sales in machine vision based products exceed $300M. Cognex became the first supplier of general-purpose machine vision to have sales exceed $100M.

From the mid to late 1980's application-specific machine vision systems were being developed to address the needs of virtually every manufacturing industry: Key Technology and Simco Ramic (now Advanced Machine Vision Corporation) for food grading and sorting applications at food processors; Design Systems a 3D system for water jet cutters and portioning of fish, poultry, and meat; Kanebo and Fuji for tablet inspection in the pharmaceutical industry; Eisai for particulate in solution detection; Ball and Inex Vision Systems a family of products for glass container inspection; Pressco and Ball, products for the metal container industry; Control Automation (now Teradyne) and IRI/Machine Vision Products populated printed circuit board inspection systems; Orbotech and others, systems to inspect bare boards; and so forth.

Since 1980, about 100 companies have been spawned that have introduced more flexible machine vision products as well as several hundred companies that now offer similar equipment with a similar complement of components dedicated to specific tasks: trace verification on printed circuit boards (Figure 2. 6) or thick-film hybrid circuits (Figure 2. 7), LED/LCD verification and evaluation systems, character readers (Figure 2.8), photomask/reticle inspection, wet- and dry-product color sorters, drop analyzers, seam tracking (Figure 2.9), particulate-in-solution analysis, tablet/capsule inspection, integrated circuit (IC) mask blank inspection (Figure 2.10), and so on. These have been designed to satisfy specific needs in specific industries.

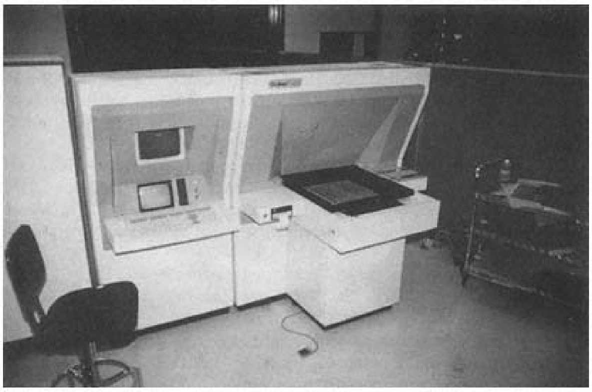

Figure 2.6
Early version of an Orbot (now part of Orbotech) printed circuit board trace inspection system.