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4—1 Evolution of Real-time Image Processing in Practical Applications

Masakazu Ejiri, Takafumi Miyatake, Hiroshi Sako,
Akio Nagasaka, and Shigeki Nagaya
Central Research Laboratory, Hitachi, Ltd.,
Kokubunji, Tokyo 185-8601, Japan

Abstract

The history of machine vision and its applications pioneered by the authors and their colleagues at Hitachi during the past three decades is reviewed. A variety of applications, especially in factory automation and office automation, were made possible by the evolution of real-time image-processing techniques. In recent years, social automation is becoming another application area of image processing, in which real-time color-video processing is expected to be a key technology.

1 Introduction

Research on "artificial intelligence" began at the Massachusetts Institute of Technology, Stanford University, and Stanford Research Institute in the US in the mid-1960s. The main concern of the researchers was the realization of intelligence by using a conventional computer, which had been developed mainly for numerical computing. At that time, a hand-eye system was thought to be an excellent research tool to visualize intelligence and demonstrate its behavior inside the computer. The hand-eye system was, by itself, soon recognized as an important research target, and it became known as the "intelligent robot". One of the core technologies of the intelligent robot was, of course, vision, and this vision research area was called "computer vision", which is now regarded as a fundamental and scientific approach to investigate how artificial vision can be best achieved and what principles underlie it.

On the other hand, research on "machine vision" was launched in the mid-1960s at the Hitachi Central Research Laboratory as one of the core technologies towards attaining flexible factory automation. Other Japanese companies also played an important role in its incubation and development. It should be noted that the word "machine vision" is preferentially used in this paper for representing a more pragmatic approach towards useful vision systems.

Though the road was not so smooth, we have fortunately achieved quite a few successes in factory automation, and also in office automation, over the last three decades. In this paper, we briefly introduce our pioneering applications of machine vision, and we discuss the history of machine vision by focusing on the image-processing technology underlying these applications. Recent technology of real-time video processing, which may be applicable to future social automation, is also explained. To begin with, the history of machine vision is illustrated in Fig. 1 and is explained in the following sections in more detail.

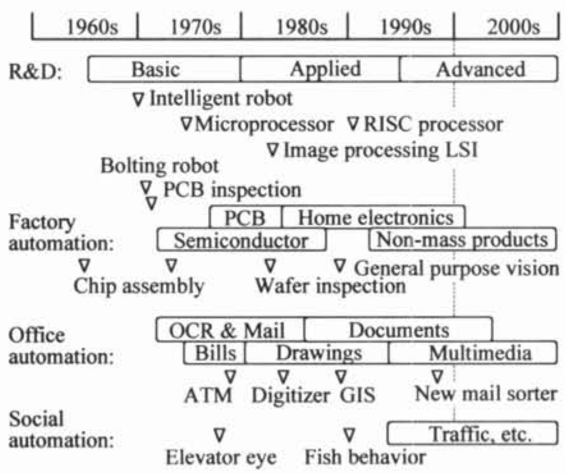

Fig. 1 History of machine vision and its applications (simplified)

2 Early Years of Machine Vision

Our first attempt at machine vision, in 1964, was to automate the assembly process (*i.e.,* wire-bonding process) of transistors. In this development, we used a very primitive optical sensor by combining a microscope and a rotating-drum type scanner with two slits on its surface. By detecting the reflection from the transistor surface with photo-multipliers, the position and orientation of transistor chips were determined with more or less 95% success rate. However, this percentage was still too low to enable us to replace human workers; thus, our first attempt failed and was eventually abandoned after a two-year struggle.

What we learned from this experience was the need for reliable artificial vision compatible to a human's pattern recognition, which quickly captures the image first, then, reduces the information quantity drastically until the positional information is firmly determined. Our slit-type optical-scanning method inherently lacked the right quantity of captured information; thus, the recognition result was apt to be easily affected by reflective noises.

In those days, however, microprocessors had not yet been developed and the available computers were still too expensive, bulky, and slow particularly for image processing and pattern recognition. Moreover, memory chips were extremely costly, so the use of full-frame image memories was prohibited.

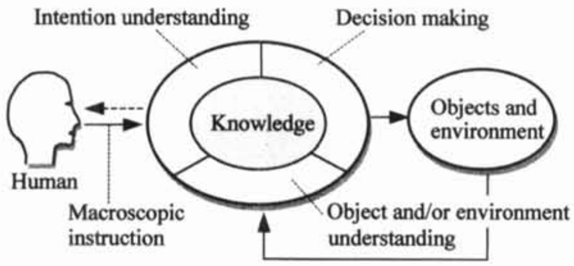

Fig. 2 Generic intelligent machine

Though there was no indication that these circumstances of processors and memories would soon improve, we started a seminal research on flexible machines in 1968. A generic intelligent machine conceived at that time is shown in Fig. 2. It consisted of three basic functions: intention understanding, object/environment understanding, and decision-making. Based on this conception, a prototype intelligent robot was developed in 1970. It could assemble blocks into various forms by responding to the objectives presented macroscopically by an assembly drawing [1]. The configuration of this intelligent robot is shown in Fig. 3.

Besides our laboratory, two other institutions, Electro-technical Laboratory (Japan) and Edinburgh University (UK), also joined in the research on intelligent robots. Therefore, six organizations in total, three in the US, two in Japan, and one in Europe, were the centers of research on computer vision and intelligent robots in the early 1970s. From then on, many research groups were founded in various institutions and companies, and computer vision and robotics became central research topics throughout the world.

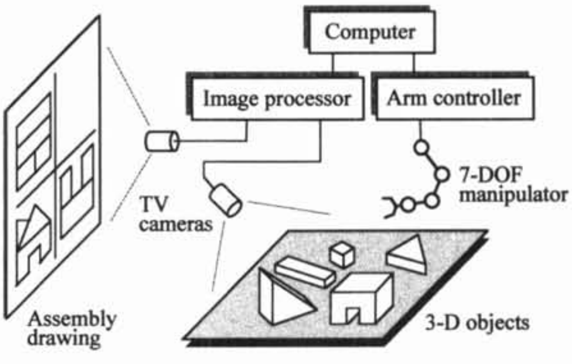

Fig. 3 Intelligent assembly robot (1970)

3 Factory Automation

Though our prototype intelligent robot in 1970 was nothing more than an expensive toy, it revealed many basic problems underlying "flexible machines" and gave us useful insights into future applications of robotics. One significant problem we were confronted with was the robot's extremely slow image-processing speed in object and environment understanding.

Our next effort was therefore focused on developing high-speed dedicated hardware for image processing, with the minimum use of memory, instead of using rather slow and expensive computers. One of the core ideas was to adaptively threshold the image signal into a binary form by responding to the signal behavior and to input it into a shift-register-type local memory that dynamically stores the latest pixel data of several horizontal scan-lines. This local-parallel-type configuration enabled us to simultaneously extract plural pixel data from a 2-D local area in synchronization with image scanning. The dedicated processing hardware for this extraction is shown in Fig. 4. Local-parallel-type logical image processing was thus the first successful solution to realize practical machine vision. By designing its logic circuit according to the envisaged purpose, the processing hardware could be adapted to many applications.

One useful yet simple method using this local-parallel-type image processing was windowing. This method involved setting up a few particular window areas in the image plane, and the pixels in the windows were selectively counted to find the background area and the object area occupying the windows.

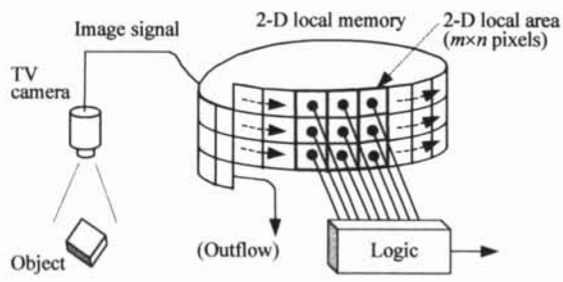

Fig. 4 Local-parallel processing hardware

In 1972 a bolting robot applying windowing was developed in order to automate the molding process of concrete piles and poles [2]. It became the first application of machine vision to moving objects. Another effective method based on local-parallel architecture was erosion/dilation of patterns, which was executed by simple AND/OR logic on a 2-D local area. This method could detect defects in printed circuit boards (PCBs), and formed one of the bases of today's morphological processing. This defect-detection machine in 1972 also became the first application of machine vision to the automation of visual inspection [3]. These two pioneering applications are illustrated in Figs. 5 and 6.

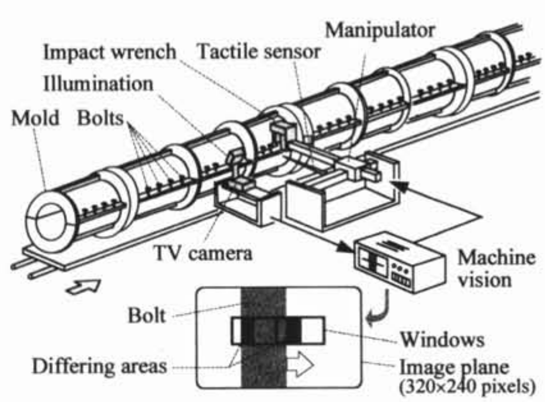

Fig. 5 Bolting robot for concrete piles/poles (1972)

Encouraged by the effectiveness of these machine-vision systems in actual production lines, we again started to develop a new assembly machine for transistors, which was, this time, based fully on image processing. Multiple local pattern matching was extensively studied for the purpose of detecting electrode positions of transistors. And by basing a local-parallel-type image processor on this matching, as shown in Fig. 7, we finally developed fully automatic transistor assembly in 1973 [4]. This successful development was the result of our ten-year effort since our first failed attempt. The developed assembly machines were recognized as the world's first image-based machines for fully automatic assembly of semiconductor devices. These machines and their configuration are shown in Fig. 8.

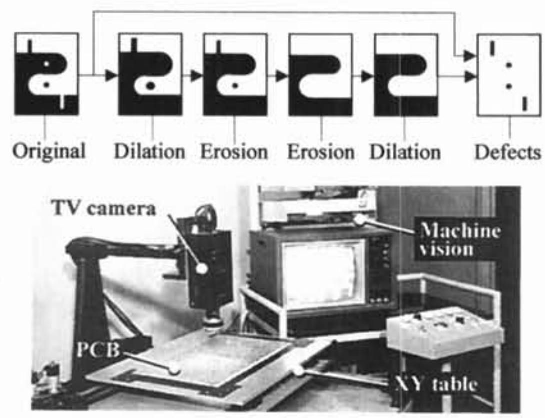

Fig. 6 Inspection of PCBs and its principle (1972)

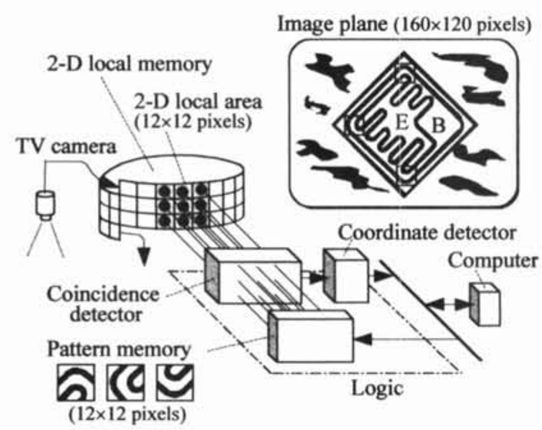

Fig. 7 Multiple local pattern matching

After this development, our efforts were then focused on expanding the machine-vision applications from transistors to other semiconductor devices, such as ICs, hybrid ICs, and LSIs. Consequently, the automatic assembly of all types of semiconductor devices was completed by 1977. This automatic assembly gained widespread attention from semiconductor manufacturers and expanded quickly into industry. As a result, the semiconductor industry as a whole prospered by virtue of higher speed production of higher quality products with more uniform performance than ever.

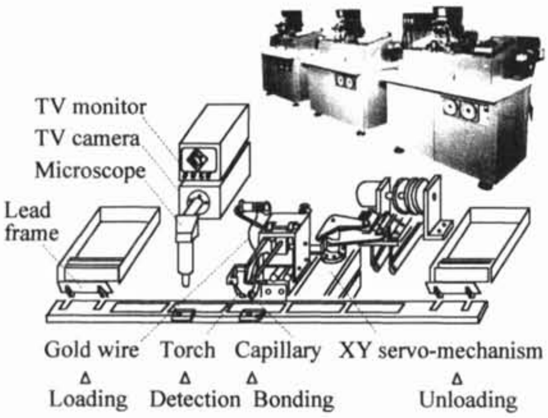

Fig. 8 Transistor assembly machine (1973)

In the mid-1970s to early 1980s, our efforts were also focussed on other industrial applications of vision technology. Examples of such applications during this period are a pump-hose connection robot, an intra-factory physical distribution system, and an inspection machine for printed marks and characters on electronic parts [5][6][7]. These examples show that the key concept representing those years seemed to be the realization of a *productive society* through factory automation, and the objectives of machine vision were mainly:

- position detection for assembly,
- shape detection for classification, and
- defect detection for inspection.

Assembly, classification, and inspection have been crucial manufacturing processes for realizing productive factories.

The most difficult but rewarding development in the mid-1980s was an inspection machine for detecting defects in semiconductor wafers [8]. It was estimated that even the world's largest super-computer available at that time would require at least one month of computing for finishing the defect detection of an 8-inch single wafer. We therefore had to develop special hardware for lowering the processing time to less than 1 hour/wafer. The resulting hardware was a network of local-parallel-type image processors that use a "design pattern referring method", shown in Fig. 9. In this machine, hardware-based knowledge processing, in which each processor was regarded as a combination of IF-part and THEN-part logical circuits, was first attempted [9].

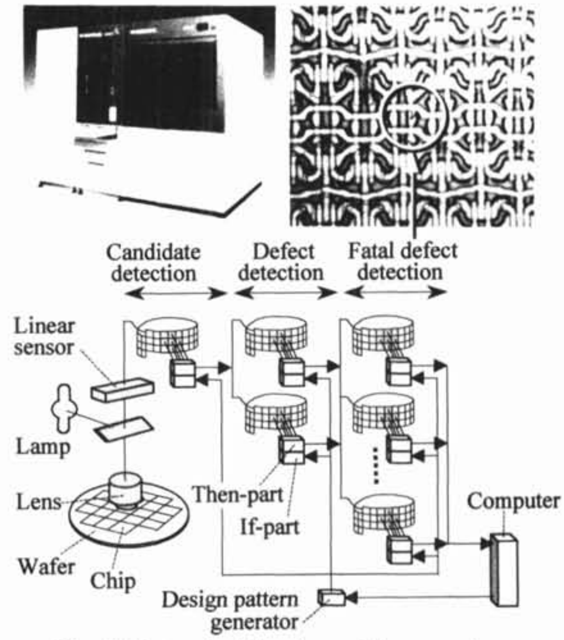

Fig. 9 Networked local-parallel processing

Meanwhile, the processing speed of microprocessors improved considerably since their appearance in the mid-1970s, and the capacity of memories drastically increased without excessively increasing costs. This improvement facilitated the use of gray-scale images instead of binary ones. And dedicated LSI chips for image processing were developed in the mid-1980s [10]. These developments all contributed to achieving more reliable, microprocessor-based general-purpose machine vision systems with full-scale buffers for gray-level images. As a result, applications of machine vision soon expanded from circuit components, such as semiconductors and PCBs, to home-use electronic equipment, such as VCRs and color TVs. A typical configuration of general-purpose machine vision is shown in Fig. 10. Nowadays, machine vision systems are found in various areas such as electronics, machinery, medicine, and food industries.

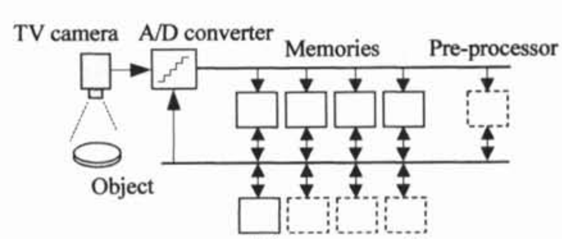

Fig. 10 Configuration of recent machine vision

4 Office Automation

Besides the above-described machine-vision systems for factory applications, there has been extensive research on character recognition in the area of office automation. For example, in the mid-1960s, a FORTRAN program reader was developed to replace key punching tasks, and mail-sorting machines were developed in the late 1960s to automatically read handwritten postal codes. However, we were not too interested in this character recognition technology until recently.

Our first effort to apply machine-vision technology to areas other than factory automation was the automatic recognition of monetary bills in 1976. This recognition system was extremely successful in spurring the development of automatic teller machines (ATMs) for banks. Due to the processing time limitation, not all of the bill image was captured, but by combining several partial data obtained from optical sensors with those from magnetic sensors, so-called sensor-fusion was first attempted and, thus, resulted in high-accuracy bill recognition with less than $1/10^{15}$ theoretical error rate.

Our next attempt, in the early 1980s, was the efficient handling of large amount of graphic data in the office [11]. The automatic digitization of paper-based engineering drawings and maps was first studied. The recognition of these drawings and maps was based on a vector representation technique, such as that shown in Fig. 11. It was usually executed by spatially-parallel-type image processors, in which each processor was designated to a specific image area. Currently, geographic information systems (GIS) based on these digital maps are becoming popular and are being used by many service companies and local governments to manage their electric power supply, gas supply, water supply, and sewage service facilities. The use of digital maps was then extended to car navigation systems and more recently to other information service systems via the Internet. Machine-vision technology contributed, mainly in the early developmental stage of these systems, to the digitization of original paper-based maps into electronic form until these digital maps began to be produced directly from measured data through computer-aided map production.

Spatially divided parallel processing was also useful for large-scale images such as those from satellite data. One of our early attempts in this area was the recognition of wind vectors, back in 1972, by comparing two simulated satellite images taken at a 30-minute interval. This system formed a basis of weather forecasting using Japan's first meteorological geo-stationary satellite "Himawari", launched a few years later.

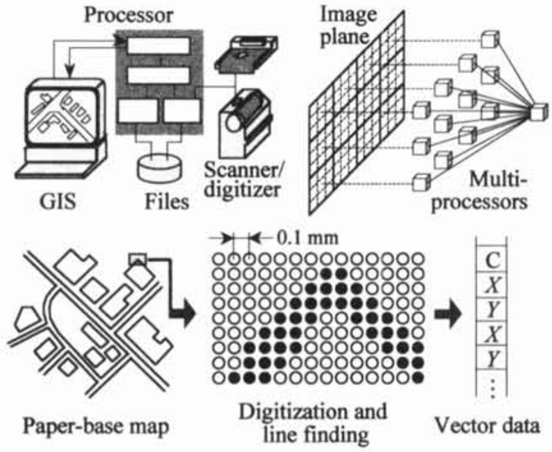

Fig. 11 Recognition of maps for geographic information systems (1984)

Research on document understanding also originated as part of machine-vision research in the mid-1980s [12]. During those years, electronic document editing and filing became popular because of the progress in word-processing technology for over-4000 Kanji and Kana characters. The introduction of an electronic patent-application system in Japan in 1990 was quite a stimulus of further research on office automation. We developed dedicated workstations and a parallel-disk-type distributed filing system for the use of patent examiners. This system enables examiners to efficiently retrieve and display the images of past documents for comparison. Nowadays, however, many application forms used in offices, such as of local government and insurance companies, continue to be hand-written by applicants. Therefore, the recognition of these various form types and the contents written in the forms is posing a challenge to further innovation.

The recognition of handwritten postal addresses is the most recent topic in machine-vision applications. In 1992, a decision was made by a government committee to adopt a new 7-digit postal code system in Japan starting from 1998. We developed new automatic mail-sorting machines for post offices in 1997, and they are now in use for daily sorting and delivery. The new sorting machine and its configuration are shown in Fig. 12. In this machine, hand-written/printed addresses in Kanji characters are read together with the 7-digit postal codes, and the results are printed on each letter as a transparent barcode consisting of 20-digit data. The letters are then dispatched to other post offices for delivery. In a subsequent process, only these barcodes are read, and prior to home delivery the letters are arranged by the new sorting machine in such a way that the order of the letters corresponds to the house order on the delivery route.

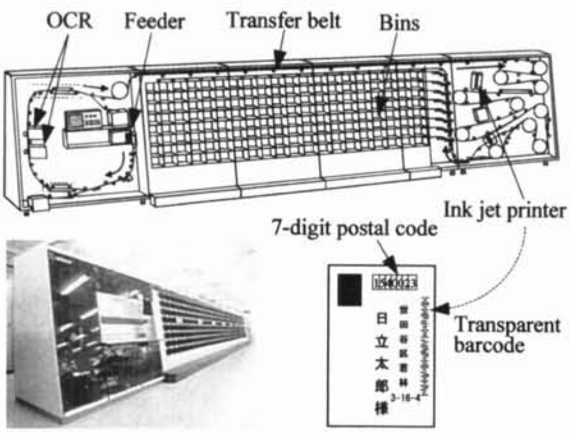

Fig. 12 New mail-sorting machine (1997)

In these postal applications, the recognition of all types of printed fonts and hand-written Kanji characters was made possible by using a multi-microprocessor-type image-processing system. A mail image is sent to one of the unoccupied processors, and this designated processor analyzes the image, as shown in Fig. 13. The address recognition by a designated single processor usually requires a processing time of 1.0 to 2.5 seconds, depending on the complexity of the address image. As up to 32 microprocessors are used in parallel for successively flowing letters, the equivalent recognition time of the whole system is less than 0.1 seconds/letter, producing a maximum processing speed of 50,000 letters/hour.

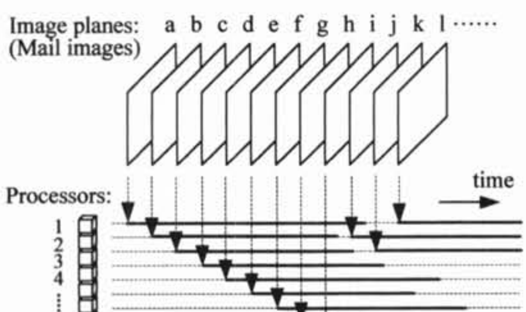

Fig.13 Temporarily-parallel processing by multi-microprocessors

The previously described office applications of vision technology show that the key concept representing those years seemed to be the realization of an *efficient society* through office automation, and the objectives of machine vision were mainly:

- efficient handling of large-scale data and
- high-precision, high-speed recognition and handling of paper-based information.

Recent progress in network technology has also increased the importance of office automation. To secure the reliability of information systems and to realize more advanced network communication systems, multi-media-type processing is becoming more important and will be one key area for intensive research and development. This processing may include image data compression, encryption, scrambling, watermarking, and personal-identification technologies.

With the progress in machine-vision technology, the size of images and the scale of processing have drastically increased, as shown in Fig. 14. The processing time needed for documents and drawings was not too restricted in the past, compared to that needed in factory automation applications. However, the present speed requirements are approaching the critical limit; thus, increasingly powerful processing technology is needed for further development in office automation.

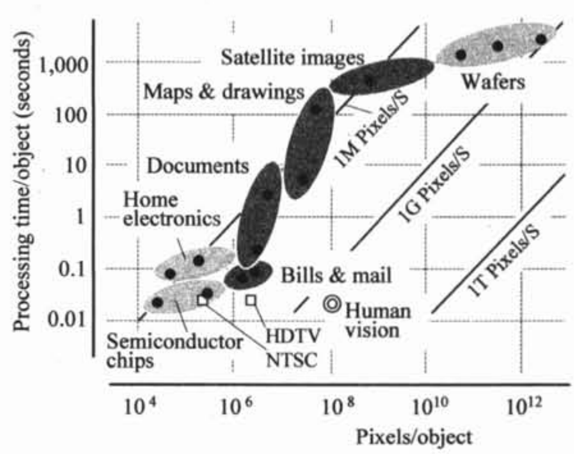

Fig. 14 Aspect of image processing in factory and office automation

5 Social Automation

In recent years, applications to social automation have become more feasible because of the introduction of new technological improvements in sensors, processors, algorithms, and networks. Probably the earliest attempt at social automation was our elevator-eye project in 1977, in which we tried to implement machine vision in an elevator system in order to control the human traffic in large-scale buildings. The elevator hall on each floor was equipped with a camera to observe each hall, and a vision system to which these cameras were connected surveyed all floors in a time-sharing manner in order to estimate the number of persons waiting for an elevator. The vision system then designated an elevator to quickly serve the crowded floor [13]. The configuration of this system is shown in Fig. 15. A robust change-finding algorithm based on edge vectors was used in order to cope with the change in the brightness of the surroundings. In this algorithm, the image plane was divided into several blocks, and the edge-vector distribution in each block was compared with that of the background image, which was sometimes updated automatically by a new image when nobody is in the elevator hall. This system could minimize the average waiting time for the elevator. Though a few systems were put into use in the Tokyo area in the early 1980s, there has not been enough market demand to develop the system further.

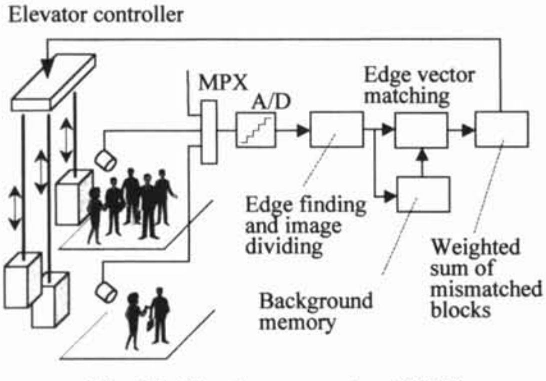

Fig. 15 Elevator eye system (1977)

More promising applications of image recognition seem to be for monitoring road traffic, where license plates, traffic jams, and illegally parked cars must be identified so that traffic can be controlled smoothly and parking lots can be automatically allocated [14]. Charging tolls automatically at highway toll gates without stopping cars, by means of a wireless IC card, is now being tested on a few highways as part of the ITS (Intelligent Transport System) project. The system will be further improved if the machine vision can quickly recognize other important information such as license plate numbers and even driver's identities.

A water-purity monitoring system using fish behavior [15] has been in operation at a river control center in a local city for the past 10 years. A schematic diagram of the system is shown in Fig. 16. The automatic observation of algae in water in sewage works was also studied. Volcanic lava flow was continuously monitored at the base of Mt. Fugendake in Nagasaki, Japan, during the eruption period in 1993. To optically send images from unmanned remote observation posts to the central control station, laser communication routes were planned by using 3-D undulation data derived from GIS digital contour maps. A GIS was also constructed to assist in restoration after the earthquake in Kobe, Japan, in 1995. Aerial photographs after the earthquake were analyzed by matching them with digital 3-D urban maps containing additional information on the height of buildings. Buildings with damaged walls and roofs could thus be quickly detected and given top priority for restoration [16].

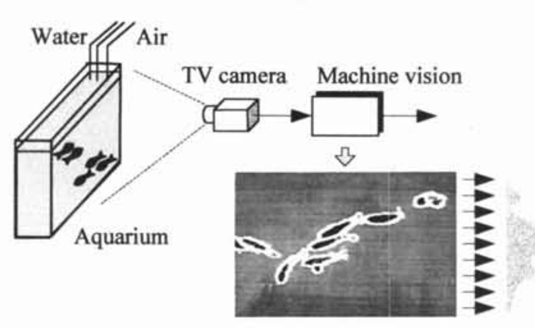

Fig. 16 Water purity monitoring from fish behavior (1990)

Intruder detection is also becoming important in the prevention of crimes and in dangerous areas such as those around high-voltage electric equipment. Railroad crossings can also be monitored intensively by comparing the vertical line data in an image with that in a background image updated automatically [17]. Arranging the image differences in this vertical window gives a spatio-temporal image of objects intruding onto the crossing. In almost all of these social applications, color-image processing is becoming increasingly important for reliable detection and recognition.

As mentioned before, the application of image processing to communications is increasingly promising as multimedia and network technologies improve. Human-machine interfaces, as already shown in Fig. 2, will be greatly improved if the machine is capable of recognizing every media used by humans. Human-to-human communication assisted by intelligent machines and networks is also expected. Machine vision will contribute to this communication in such fields as motion capturing, face recognition, facial expression understanding, gesture recognition, sign language understanding, and behavior understanding.

In addition, applications of machine vision to the field of human welfare, medicine, and environment improvement will become increasingly important in the future. Examples of these applications are rehabilitation equipment, medical surgery assistance, and water purification in lakes.

Thus, the key concept representing the future seems to be the realization of a *calm society*, in which all uneasiness will be relieved through networked social automation, and the most important objectives of machine vision will eventually be the realization of two functions:

- 24-hour/day abnormality monitoring via networks and
- personal identification via networks.

In most of these social applications, dynamic image processing, which analyzes video images in real-time, will be a key to success. There are already some approaches for analyzing incoming video images in real-time by using smaller-scale personal computers. One typical example is our "Mediachef", which automatically cuts video images into a set of scenes by finding significant changes between consecutive image frames [18]. The principle of the system is shown in Fig. 17. This is one of the essential technologies for video indexing and video-digest editing. To date, this technology has been put into use in the video inspection process in a broadcasting company so that subliminal advertising can be detected before the video is on the air.

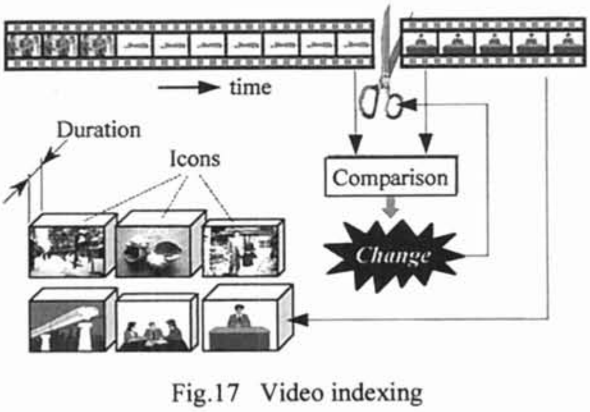

Fig.17 Video indexing

For the purpose of searching scenes, we developed a real-time video coding technique that uses an average color in each frame and represents its sequence by a "run" between frames, as shown in Fig. 18. This method can compress 24-hour video signals into a memory capacity of only 2 MB. This video-coding technology can be applied to automatically detect the time of broadcast of a specific TV commercial by continuously monitoring TV signals by means of a compact personal computer. It will therefore allow manufacturers to monitor their commercials being broadcast by an advertising company and, thus, will provide evidence of a broadcast.

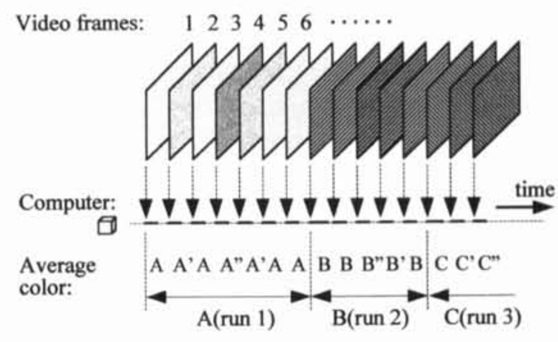

Fig. 18 Real-time color video coding

A real-time creation of panoramic pictures may also be an interesting application of video-image processing [19]. A time series of each image frame from a video camera during panning and tilting is spatially connected in real-time into a single still picture, as shown in Fig. 19. Similarly, by connecting all the image frames obtained during

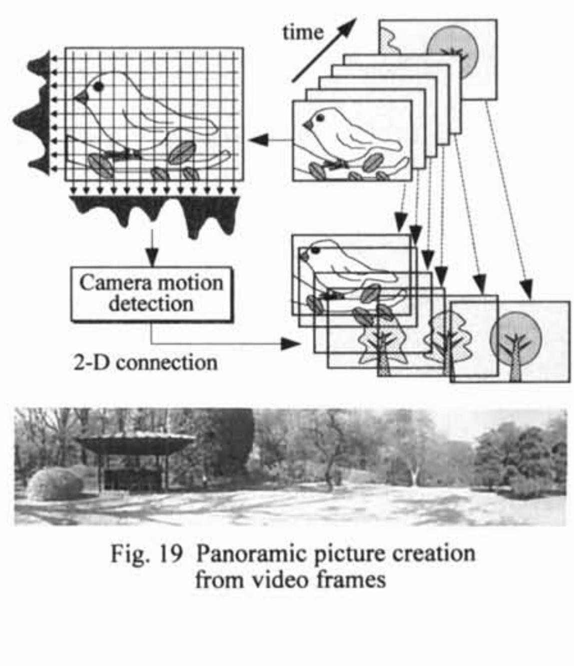

Fig. 19 Panoramic picture creation from video frames

the zooming process, a high-resolution picture (having higher resolution in the inner areas) can be obtained.

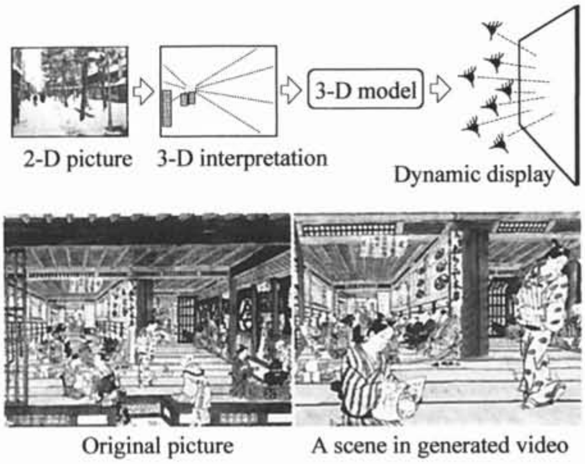

Fig. 20 TIP (tour into the picture) technology

Another example of dynamic video analysis is "Tour into the picture (TIP)" technology. As shown in Fig. 20, a 2-D picture is scanned and interpreted into three-dimensional data by manually fitting vanishing lines on the displayed picture. The picture can then be looked at from different angles and distances [20]. A motion video can thus be generated from a single picture and viewers can feel as if they were taking a walk in an ancient city when an old picture of the city is available.

The technology called "Cyber BUNRAKU", in which human facial expressions are monitored by small infrared-sensitive reflectors put on a performer's face, is also noteworthy. By combining the facial expressions thus obtained with the limb motions of a "Bunraku doll" (used in traditional Japanese theatrical performance), a 3-D character model in a computer can be automatically animated in real-time to create video images [21], as shown in Fig. 21. This technology is now being used to create multimedia programs much faster than through traditional methods.

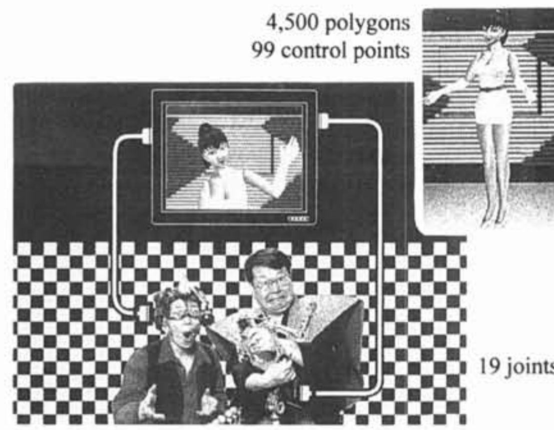

Fig. 21 Cyber-BUNRAKU technology

We have given a few examples of real-time image processing technologies, which may be applicable to social automation in the future. The most difficult technical problem facing social automation, however, is how to make robust machine-vision systems that can be used day or night in all types of weather conditions. To cope with the wide changes in illumination, the development of a variable-sensitivity imaging device with a wide dynamic range is still a stimulating challenge. Another key towards

Table 1 Progress of machine vision research (simplified)

	Past	Present	Future
Main application area	Factory automation	Office automation	Social automation
Key concept	Productivity	Efficiency	Calmness, relief from uneasiness
Main research topics	Detection of positions shapes defects	Mail address reading Bill recognition Document understanding Drawing understanding	Personal identification Abnormality monitoring Face and facial expression analysis Behavior understanding
Killer applications	Semiconductor PCB Home electronics	Mail sorter ATM, GIS Document reader Multimedia system	Traffic use Communication use Welfare, medical, and environmental use
Key technologies	Windowing Pattern matching Feature extraction	Vector conversion Data structuring Context analysis	Real-time video analysis Sensor fusion Networked vision technology
Features of image processing	Local-parallel Binary > gray	RISC-based processing Gray > binary	Single, Parallel, Embedded Color

achieving robust machine vision will be the establishment of sensor-fusion technology, which combines image information with other information obtained from a variety of different sensors.

6 Summary

The history of machine vision research was briefly reviewed by mainly focusing on the topics we have studied at Hitachi. We can say that the progress in factory automation and office automation has been greatly advanced by the evolution of machine-vision technology, which has also been affected, in turn, by the progress of memory technology and processor technology. The features of machine vision in the future, together with (and in contrast to) those of the past and present, are summarized in Table 1. In the future, the real-time analysis of color video images will be an important key for realizing the *calm* society through networked social automation and will, thus, be a central topic for future research on machine vision.

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