MACHINE VISION AND ROBOTICS: INDUSTRIAL REQUIREMENTS

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I INTRODUCTION

It is hardly necessary to emphasize the importance of visual sensing and interpretation in human activities. We can appreciate the severe handicaps and limitations imposed on the mental and physical activities of the blind, often ameliorated to varying degrees by laborious training of tactile, auditory, and olfactory sensory capabilities. The importance of human vision is a major motivation for the intense interest in and significant research effort devoted to machine vision. For the past 15 years the artificial intelligence community has been slowly developing its understanding in this field of research [1-11] and has begun to implement simple but increasingly sophisticated machine vision techniques for use in many fields, such as manufacturing processes, medical diagnosis, photo-interpretation, and military missile guidance.

Machine vision research, in common with most of the work done in artificial intelligence, is still being conducted primarily as an experimental science. Certainly, fundamental principles in physical optics, electronics, and computer science are employed to good advantage in acquiring and processing images, but the interpretation of such images for pragmatic use depends to a great degree on a large and growing number of algorithms and methods -- heuristically conceived, rationally extended, and experimentally verified.

It is the author's opinion that we cannot wait to "solve" the machine vision problem in general by establishing a relatively comprehensive theory. It appears more sensible to make full use of what is known, applying the rich accumulation of methods to situations in which simplifying physical constraints can be applied to yield economically viable solutions. Fundamental machine vision research should proceed vigorously, generating new knowledge and techniques, because such understanding is basic to the solution of difficult problems. At the same time, applied research and development resulting in solutions to simpler, more constrained but general classes of tasks will, at the very least, impart credibility to the field. More importantly, this approach may indicate new strategies and directions to explore in concurrent research on the more fundamental issues of machine vision.

In this paper I have attempted to select major classes of industrial-context problem areas in which successful application of machine vision will have a significant, if not revolutionary, impact on productivity, product quality, and even the mass-production process itself. Although the grouping of tasks within each class is somewhat arbitrary, the classes themselves are real, having been identified and described by competent factory personnel during visits to plants and in subsequent discussions between the author and his colleagues over the past six years. Furthermore, there are sufficient instances with comparable requirements in each class to justify application of general rather than ad-hoc techniques.

Two broad groups of applications are described in the next sections. The first group includes applications in which machine vision can be an essential part either of a manipulative task involving industrial manipulators (robots) or of the control functions in a production process. In the second group, machine vision supplants or supports the human in performing inspection for quality control, minimizing production of scrap and improving safety. Manipulation may be involved in the second group, but primarily for the purpose of presenting workpieces or assemblies to the vision system.

II MACHINE VISION FOR SENSOR-CONTROLLED MANIPULATION

For over 15 years programmable manipulators (industrial robots) have been performing important but fairly simple manipulative tasks, such as loading, and unloading other machines, stacking parts, spot-welding, paint-spraying, and so forth [12]. In a few applications, mostly in the laboratory, these robots have begun to be employed for assembly, material handling, and other fabrication processes with the aid of sensory feedback [13-22]. The positioning and orientation of workpieces, assemblies, packing boxes, and machines to be served must be known with considerable precision, usually requiring expensive jigs, fixtures, and elaborate conveyors. Examples of some applications in factories are the force feedback and compliant wrist used by Hitachi for assembly [23]; force sensing used by Olivetti for assembly [24,25]; visual feedback used by Cheseborough Ponds for process control [26]; and noncontact eddy-current sensory feedback used by Hitachi for path control in arc-welding [27]. To date there does not exist a commercially available, fully programmable industrial robot capable of using, as needed, _all_ of the available sensory feedback systems, in particular the machine vision system.

Figure 1 is a summary of desired functions for machine vision applicable to sensor-controlled manipulation. In the succeeding sections the application of these functions to various classes of manipulative tasks will be described.

Representative task areas are summarized in Figure 2. Machine vision can be applied in an effective and economic manner to permit industrial robots to deal with imprecisely positioned or unoriented workpieces and assemblies, to compensate for buildup of errors in tolerances and, in general, to enable the robot to "fine-tune" its end-effector to correct adaptively for unforeseen changes in the position and orientation of workpieces. It should be added that in many instances the use of the compliant wrist and of force/torque and tactile sensing may be also indicated, especially where the positive action of contact sensing enables a precision unobtainable with relatively low-resolution cameras.

- RECOGNITION OF WORKPIECES/ASSEMBLIES AND/OR RECOGNITION OF THE STABLE STATE WHERE NECESSARY.
- DETERMINATION OF THE POSITION AND ORIENTATION OF WORKPIECES/ASSEMBLIES RELATIVE TO A PRESCRIBED SET OF COORDINATE AXES.
- EXTRACTION AND LOCATION OF SALIENT FEATURES OF A WORKPIECE/ASSEMBLY TO ESTABLISH A SPATIAL REFERENCE FOR VISUAL SERVOING.
- IN-PROCESS INSPECTION — VERIFICATION THAT A PROCESS HAS BEEN OR IS BEING SATISFACTORILY COMPLETED.

FIGURE 1 DESIRED FUNCTIONS OF MACHINE VISION FOR SENSOR-CONTROLLED MANIPULATION

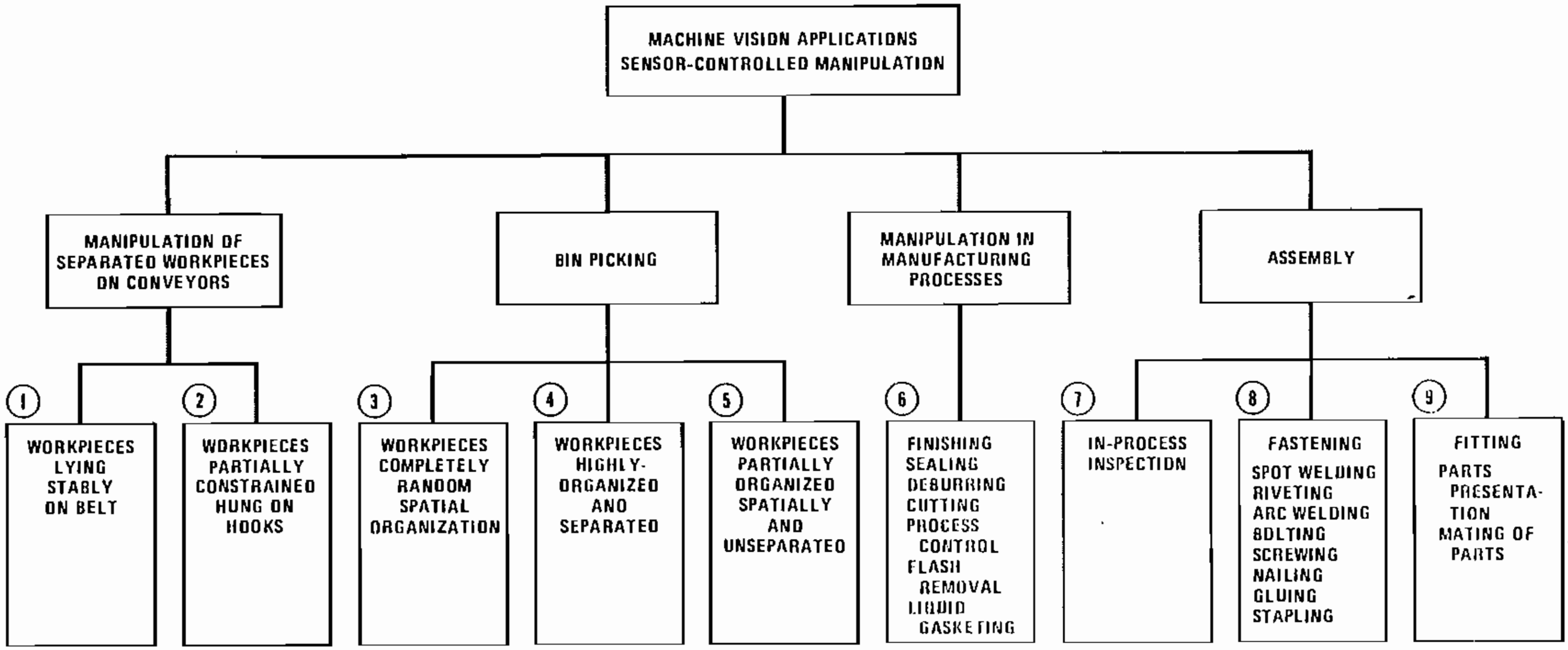

FIGURE 2 MACHINE VISION APPLICATIONS — SENSOR-CONTROLLED MANIPULATION

A. Manipulation of Separated Workpieces on Conveyors

There are many instances in which individually separated parts, sub-assemblies, and assemblies are transported by overhead or belt conveyors from station to station in the factory. The workpieces are more often than not randomly oriented and positioned, because this is the least expensive way to move them. Occasionally they can be quite close to and even in contact with one another. If they are piled more than one layer thick, simple passive mechanical means can usually be devised to unscramble them and maintain a single layer. It may be necessary to acquire each workpiece with a manipulator and to transport it for packing in a prescribed order and state in a container, for feeding into another machine with a prescribed position and orientation, or for sorting, as in a batch of mixed workpieces. Two general subclasses can be distinguished: separated workpieces lying stably on a belt, and workpieces hung on hooks.

(1) Separated Workpieces Lying Stably on a Belt: For many cases in which workpieces are lying stably on a belt and there is an unobstructed view of each individual workpiece (even though they may be touching), it is feasible to apply available simple machine vision techniques to perform one or more of the following:

- Identify the workpiece
- Determine the stable state of the workpiece
- Determine the relative position and orientation of the workpiece

Successful use of binary (black and white) visual information depends critically on carefully engineering illumination and control of background. This is necessary to provide a high-contrast image for extraction of a two-dimensional outline reresenting the shape and major internal features of the workpiece for each stable state [28]. These techniques can be successfully applied on a belt moving with variable speed, using flash photography. When sufficient contrast cannot be obtained, more sophisticated picture-processing methods are available, but have yet to be applied in industry. These include the potential use of (1) gray-scale imaging, (2) intense patterned or structured light with known geometry projected onto the workpiece to create a contrasty pattern against the background, and (3) ranging techniques to permit extraction of the outline from range rather than intensity data, or if necessary, the use of both intensity and range data.

(2) Workpieces Hung on Hooks: If the workpiece is being transported by an overhead chain conveyor or the equivalent, the machine vision techniques just discussed will not suffice. Usually the workpiece is crudely supported, requiring three-dimensional information to determine its position and orientation in space. One solution to this problem is to use more expensive supports, guaranteeing unique positioning and orientation in space, and eliminating sway and rotation as much as possible. A more general solution is to add some form of range sensing to existing two-dimensional intensity sensing. Again, the use of structured light or other optical ranging techniques may be feasible options.

In most factories a great many human workers are involved in the transport and handling of workpieces, and it is rare that the expense of special magazines or jigged fixtures for maintaining precise, known workpiece positioning and orientation can be justified. In batch production (and when there is frequent model change) use of special fixtures may become even more expensive. Thus, it is highly desirable to develop techniques using machine vision that is readily reprogrammable and generally applicable to many initial and modified situations.

At present this application of machine vision is most highly developed for dealing with workpieces of the first subclass--that is, those that are, or can be, separated, and that lie stably but unoriented either on moving belts or on a stationary support structure. A relatively inexpensive vision system consisting of a solid-state television camera (with a resolution of approximately 128 x 128 elements) and a microcomputer or miniprocessor, can perform the required visual sensing for a wide range of tasks [16]. Software developments over the past five years are adequate to meet many performance requirements, such as a total time of under a half-second for acquiring and processing a picture. By adding a specialized preprocessing hardware, on-line processing can be reduced to approximately two hundred milliseconds There is little doubt that this performance can be significantly enhanced by carefully engineered systems designed for a single specialized task. One can predict that within two years the cost of such a vision system will not add more than 10% to 15% to the cost of a fully programmable robot system.

For the second subclass of workpieces--those that are hung, partially constrained, on hooks or the equivalent--a considerable research and development effort is needed. Range sensing obtained by passive or active means can help solve this problem in a direct manner, general in application, yielding three dimensional information on the position and orientation of workpieces _in space_ [29,30,31].

B. _Bin Picking_

Another common method of transporting and buffer-storing workpieces in factories is in containers or bins. Three major classes can be distinguished:

1. _Bin Picking--Workpieces in Completely Random Spatial Organization_

The workpieces are jumbled in a container, sometimes interlocked, randomly positioned and oriented, with no clear, unobstructed view of most of the workpieces. This method of transport and buffer storage is the most common, being the least expensive method for rugged workpieces that can withstand some degree of marring or scratching without degradation of quality, performance, or reliability.

2. _Bin Picking--Workpieces Highly Organized Spatially and Separated_

The workpieces have to be handled carefully to prevent damage to delicate details, or they have exposed, finely machined or finished surfaces that should not be scratched or dented. In this class the workpieces are usually arrayed in separate compartments within a bin lined with protective material to prevent damage during transport (e.g., "egg-crate" compartments). Often there are several layers of workpieces in depth in the same bin, with protective material between layers. Each workpiece separated from its neighbors is usually in a known stable state and, although not positioned and oriented precisely, the permitted variations or "slop" in these parameters are small. We will not consider the extreme of this class, which involves the use of expensive jigs or magazines to prevent damage and maintain precise positioning and orientation during transport and robot acquisition.

3. Bin Picking--Workpieces Partially Organized Spatially and Unseparated

A third class, quite common in practice, includes workpieces disposed with a degree of organization intermediate between the random arrangement of the first class and the very orderly arrangement of the second class. The workpieces are piled in a bin in a crudely ordered array without protective interlayers or separators, often several layers in depth. Usually each workpiece is not in one of the easily recognizable stable states that occur when it is lying on a flat surface. Each workpiece, however, is often aligned with its neighbors, with its position and orientation considerably more predictable than with the completely randomized organization of the first class.

The general problem of automating the handling of workpieces is the same for these three classes--workpieces must be acquired one at a time and then presented to some other location with a predetermined position and orientation in space. Applications include sorting and packing, loading workpieces into another machine or process, and presenting parts for assembly. At present one has to rely on sophisticated human visual and tactile capabilities in those instances in which bowl orienters/feeders and other feeders cannot be used successfully, because of the size, weight, delicacy, or other properties of the parts. Machine vision, augmented as needed with other sensors and devices, can be applied effectively to a subset of these classes now, with promise of future extension to the other applications.

A high level of picture processing and interpretative capability is required for dealing with completely jumbled and random workpieces. The vision system has to cope with poor contrast, partial views of parts, an infinite number of stable states, variable incident and reflected lighting, shadows, geometric transformations of the image due to variable distance from camera lens to each pat, etc. These are formidable problems in scene analysis, with some initial success reported by General Motors [32]. Progress will be slow, and practical implementation will require considerably faster and less expensive computational facilities than are presently available.

An approach that finesses many of these problems is to divide the problem of completely disoriented workpieces into two stages. First, remove a few (one or more) of the workpieces at a time from the bin, deposit them with random position and orientation--separate and lying stably on a flat contrasty surface--and then apply known simple machine vision techniques to determine the identity, stable state, position, and orientation of each separated workpiece. Machine vision will thus provide the necessary information for controlling a second and final acquisition by a robot. The first gross acquisition of a few workpieces can be assigned to an inexpensive manipulator, since there is no need at that point for precise positioning and orientation. Initial work on this approach has been reported by SRI International [16]. A somewhat different approach, in which the parts orientation and position in space are determined while the part is held by the robot, has been reported by the University of Rhode Island [33]. It remains to be shown that these methods can be acceptably implemented for a large class of workpieces. The method of first effecting separation and then accomplishing recognition will certainly be acceptable for large, heavy parts with ample time between successive operations.

Simple machine vision techniques appear adequate for the second class described above, in which separated, partially oriented workpieces are arranged in orderly arrays. It will be necessary to devise software able to differentiate between the workpieces and the egg-crate enclosing walls (if present)—a complication that appears surmountable. If necessary, inexpensive bins can be used, especially designed for simplifying the visual processing by either enhancing contrast or providing a known geometric background. Control of incident lighting, including the use of appropriate filters may also constitute a useful means of simplifying the acquisition of suitable workpiece images.

The third class of semiorganized workpieces can be handled by the method of first separating the workpieces and then applying simple machine vision techniques, as described above. Since the workpieces are somewhat aligned and partially organized, separating them is simplified to some degree, with the possibility of reducing the time required for a complete operation. In fact, in considering costs of the total system, it may be feasible in many instances to pack parts that do not require surface protection in this semiorganized fashion, since a robot can be used to pack the parts in the bin at the station where the parts originate (the foundary, receiving, or the machine shop). Standardization in methods of handling can reduce the number of different robot-handling systems, with ensuing economies in maintenance, setup time, and inventory of replacement parts and machines.

Binpicking is a universal process in almost all factories and represents one of the best candidates for the introduction of sensor-controlled manipulation. Assuming the availability of an inexpensive low-resolution vision system and less costly industrial robots, many binpicking tasks can be accomplished economically within the state of the art today. A good prospective system would be composed of a vision module, a modified limited-sequence robot, and a servoed X-Y table, all under microcomputer control [34]. At present unit retail prices, such a system would cost approximately $30,000 to $35,000--considerably less if mass-produced.

C. Vision-Controlled Manipulation in Manufacturing Processes

In batch production involving discrete parts, a large number of important manufacturing processes cannot be economically automated, because the cost of specialized jigs and "hard"-automation production machines is prohibitively high for the small number of workpieces or assemblies in each batch. Programmable automation based on the use of robots has already proved its worth in spotwelding (an assembly process) and automated paintspraying (a finishing and/or surface protection process). This type of automation is being introduced into many production lines by major companies throughout the world. Under pressure of government regulations in this country, and because of the expense of coping with undesirable and unhealthy environmental conditions associated with noxious vapors and fumes, automated paintspraying equipment will essentially replace human workers, wherever economically feasible, within the next ten years.

In paintspraying and similar applications, there still is universal reliance on relatively costly control of workpiece positioning during painting. Since the majority of spraypainting lines do not have specialized conveyors to eliminate uncertainty in positioning and orientation, there exists a need for sensors, preferably noncontact, to effect these adaptive corrections. Machine vision in its present implementation is applicable if two-dimensional information suffices. However, in most cases there is a need for three-dimensional processing to locate a workpiece or assembly in space, thus requiring range as well as intensity information. As previously observed, key requirements for an acceptable machine vision system are that its cost should not add more than 10% to 25% to the robot cost, and that for moving lines the required sensing information be supplied in a fraction of a second (0.2 to 1.0 second). For production lines in which the workpiece or assembly can be stationary during painting, this permissible time for visual processing can be extended to several seconds.

Although paintspraying is a currently popular application, similar finishing applications include sandblasting and spraying of protective chemical coatings on selected areas of the workpieces.

A subclass of manufacturing processes that have common machine vision requirements includes the application of semiliquid sealants, deburring and removal of flash from castings and moldings, torch cutting, laser machining, and liquid gasketing. These applications require tool path control along paths that are specified in relation to defined edges, seams, or other features of the workpiece. By reason of variations in tolerance and fit, these paths are not precisely predetermined; therefore each operation is unique within narrow limits, requiring continuous servoing of the tool. In flash removal and sealing the amount of material to be removed or added is often variable with position, requiring more elaborate image processing for automatic control of these variables as well as path control. For many of these applications two-dimensional image processing suffices; with the addition of a proximity sensor, air-pressure sensing, or contact sensing, many contoured workpieces with relatively uncomplicated surfaces can be accommodated. The general case, however, requires three-dimensional servoing, for which range information would be essential. The cost/time requirements are similar to those previously mentioned for paintspraying.

It should be noted that efficient computational algorithms are available to provide control functions for adaptively correcting the path of a tool carried by a multi-degree-of-freedom robot. These algorithms are included in programs that can be executed on-line for:

(1) Interpolation--piecewise linear approximations of continuous-path trajectories.

(2) Path smoothing--elimination of abrupt changes in the trajectory [16].

(3) Transformations from robot to world-coordinate systems and the converse [14], including moving-line coordinate systems.

D. Vision-Controlled Manipulation in Assembly

The Bureau of Census reported (in Occupation by Industry, PC2-7C) that for 1970 production workers, not including overhead staff, constituted from 40% to 65% of the total workers engaged in the manufacture of durable goods. Assembly workers, comprised approximately 17%, and inspection workers approximately 10% of production personnel. These percentages do not include other workers, such as welders, painters, material handlers, packers, etc., who may be affected by the new technology. The development of programmable automation tools and techniques for automating batch assembly has therefore become a desirable major goal with highly significant economic and social consequences. Furthermore, there are interesting and useful byproducts of these studies resulting from the disciplined analysis that is mandatory if a computer is to control correctly every step in assembly. We tend to take for granted the human assembler's accumulation of rich world experience coordination, dexterity, and adaptablility. For computer control however, no detail can be omitted. Thus, the analysis needed to implement a total assembly system for computerized robots can actually lead to an improved and simplified assembly system for humans. Moreover, when any manufacturing process, including assembly, is brought under precise computer control, it becomes possible to improve and maintain product quality to any practical and affordable limit.

Machine vision has as important a role in automated assembly as human vision has for assembly by humans. The desired vision functions, as described in Figure 1, are all applicable to assembly. Following are brief descriptions of how they can facilitate and simplify the assembly process:

(1) Machine vision enables parts and subassemblies to be identified, acquired, and presented in a predetermined manner to mate with other parts or assemblies. These come under the heading of "fitting" processes.

(2) Machine vision can provide feedback to control adaptively the position of robot assembly tools to be used for fastening, eliminating many costly jigs. This function has been labeled active accommodation, implying that errors in position and orientation are sensed, and the

tool (or part) is repositioned as part of an active servo loop. This correction is relatively coarse and, where necessary, fine tuning of such corrections can be effected by using passive accomodation, in which a compliant wrist [35] corrects for the remaining error in position and orientation through the effect of reaction forces and torques on the tool.

(3) Machine vision can continuously control the path of a robot-held tool along a designated line or curve whose trajectory is described in relation to either a workpiece edge or other salient feature.

(4) Machine vision can perform the essential function of in-process inspection. It can verify that the correct parts are being mated and that each step has been completed satisfactorily without damage. When augmented by contact sensors, such as displacement, force, and torque sensors, the proper seating of mating parts and the desired degree of tightness of bolts and screws can be monitored as well.

For convenience, assembly operations can be classified into two broad groups under the headings of fastening and fitting. Utilization of machine vision in these operations will now be discussed.

1. <u>Fastening</u>

The most common fastening methods are spotwelding, riveting, arcwelding, bolting, screwing, nailing, stapling, and gluing. The major vision requirement is to control the position and orientation of the fastening tool carried by the robot in relation to the workpieces, which may be stationary or on moving conveyors. The same considerations obtain that were described previously under the heading, "Vision-Controlled Manipulation in Manufacturing Processes". Essentially, machine vision can sense the position and orientation of workpieces or salient features of workpieces, eliminating the need for costly jigging.

In bolting and riveting the insertion of bolts and rivets in holes can make use of both active and passive accommodation to correct adaptively for alignment errors. Spotwelding, screwing, nailing, stapling, and gluing can utilize the path control function of machine vision when the location and trajectory of the line of fastenings are variable because of buildup of manufacturing tolerances or poor fit. Corrections to a stored robot program can be generated and new tool trajectories calculated in real time. Here too the cost should not exceed 10% to 15% of the cost of the robot, and the total time required for sensing and interpretation should be in the range of 0.1 to 1 second.

The automation of electric arcwelding is of particular interest, because the working environment is generally deleterious for humans and this highly cost-effective method of fastening is not readily replaceable. Machine vision is a good candidate sensor for controlling the torch path and supplying the essential information to control weld parameters in correcting for poor fit, heat distortion, etc. of the parts to be mated.

In all these fastening operations machine vision can verify the satisfactory completion of each fastening step, if such inspection is desired and is cost-effective.

2. Fitting

For fitting operations in assembly systems in which the use of jigs is to be minimized, the primary functions in which machine vision can be useful are parts presentation and the mating of parts. Identification of each part or of the stable state of each must be effected if the parts, or several different types of parts, are buffer-stored randomly in bins or on endless belts. In addition, each part must be sequentially presented and fitted to the rest of the assembly in progress, requiring determination of the relative orientation and position of the main assembly and each part of the subassembly. Finally, in-process visual inspection can monitor the successful completion of each step.

It should be noted that machine vision can be dispensed with entirely, with reliance on contact sensing only for monitoring of fitting for step completion, and for making minor adjustments in position and orientation. However, this strategy requires elaborate control of the position and orientation of each component part, with no means of adapting to errors caused by tolerance buildup. Modifications or model changes would require reworked or new special jigs, as well as a modified software program. This reduced changeover flexibility must be compared with the additional one-time cost of a machine vision system, especially in terms of lost production time.

III MACHINE VISION FOR INSPECTION

Economically priced solid-state television cameras in the form of unidimensional linear and two-dimensional planar arrays are now commercially available. Their advantages over vidicon-type cameras include small size, inherent ruggedness, stability, discrete photoelectric elements that can be individually addressed, and compatibility with computer hardware. Inspection of all kinds occupies approximately 10% of production workers in the manufacture of durable goods, and is an essential function (often implicit) in the service industries as well. Picture-processing software developed over the past 15 years can now be applied practically to many inspection problems in which the optical-image information can be extracted and interpreted in rich detail. We can expect these systems to become extensively used in factory and commerce as the discrete photocell, which is primarily a binary on-off sensory device with no imaging capability.

Machine vision applications to inspection can be classified into two large groups: inspection requiring highly quantitative mensuration, and inspection that is primarily qualitative but frequently includes semiquantitative mensuration. Many inspection tasks of the second group are implicit--that is, they are performed by workers as part of some other job (e.g., an assembler makes certain that the right parts, complete and undamaged, are being assembled). This classification and its subdivisions are shown in Figure 3. Applications within each group will now be discussed.

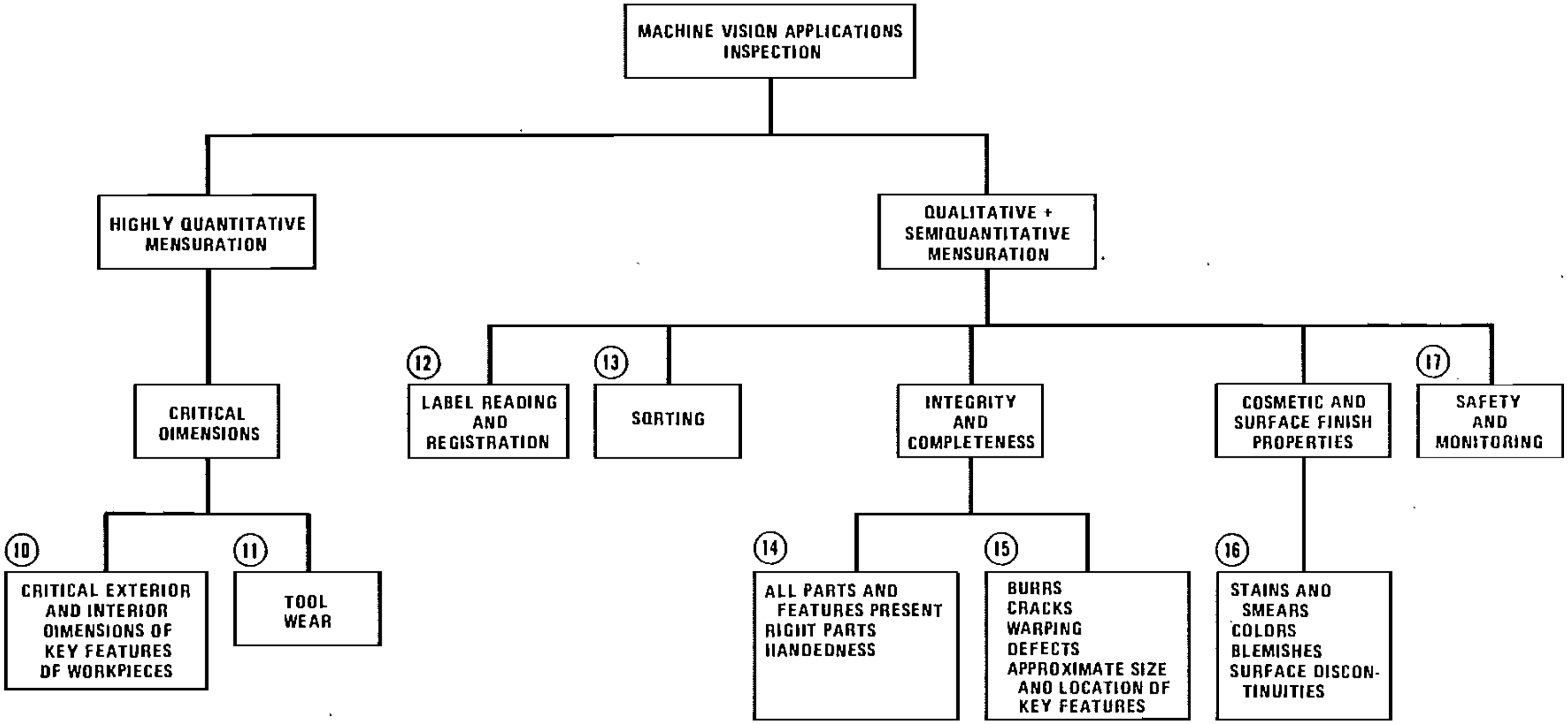

FIGURE 3 MACHINE VISION APPLICATIONS — INSPECTION

A. Inspection Requiring Highly Quantitative Mensuration

The mass-production process depends to a great extent on maintaining critical dimensions of workpieces within given tolerances. Many methods of measurement by means of mechanical devices are currently in universal use, such as micrometers, dial gauges, vernier calipers, Johanssen blocks, go/no-go gauges, and special measuring jigs. Where hard automation is implemented for large production runs it is sometimes possible to automate these mechanical measurements as part of in-process inspection for quality control and to limit the production of scrap, as, for example, in detecting the breaking of a die in a progressive stamping machine. In many instances, because of the time required for this additional inspection operation, the throughput of an expensive machine is reduced and therefore 100% inspection is not warranted. Quality control then consists of establishing statistically-based techniques, with manual inspection of a small sample of produced workpieces. In batch production such inspection is generally performed manually, whether 100% or sampled. There is, therefore, a need to develop techniques that are sufficiently precise, easily programmable for modifications or model change, and noncontact--so that the sensor is nonintrusive to the mechanical fabrication and/or assembly process. Flying-spot laser scanning techniques are being successfully used for this purpose, but appear of limited value for general application.

1. Machine Vision for Quantitative Inspection

The solid-state linear-diode array and the two-dimensional camera interfaced with microprocessors or microcomputers provide powerful general-purpose tools for accurate noncontact, nonintrusive mensuration at potentially low cost. By careful selection of the optical coupling between camera and workpiece, the full resolution of low-resolution cameras can frequently be utilized, ranging from microscopic to macroscopic fields of view. The discrete nature of the optoelectronic sensing elements and the insensitivity to line voltage variations, as well as, to variability and nonlinearity of line scan, enable a superior, more precise means of mensuration by substituting digital counting techniques for analog measurements.

The relatively inexpensive linear-diode array, available with up to a thousand elements along one dimension, is generally applicable where the workpiece to be inspected is in motion and thus capable of generating a two-dimensional when scanned perpendicularly to the motion. The flow of data can be processed "on the fly", a line at a time or after a complete two-dimensional image has been buffer-stored in computer memory. Extraction of salient dimensions to be measured can be effected with special high-speed hardware or, more commonly, by software.

The two-dimensional array camera can obtain a two-dimensional image of a workpiece, whether stationary or in motion, with high intensity flash-lamp operation possible for minimizing blurring. Processing of the image can be effected in a manner similar to that of the linear array. Available cameras are somewhat limited in resolution, ranging from under 100 to 500 elements in one dimension. We have found a 128 x 128 element camera quite adequate for a broad range of applications [16].

In employing these cameras for inspection there is always the problem of positioning the workpiece for viewing. Although precise positioning and orientation can often be compensated for by suitable software, placement into coarse position may require specialized manipulation, not always cost-effective. The combination of an inexpensive limited-sequence robot, a programmable X-Y table, and a camera--all controlled by a microcomputer--may be a general-purpose solution [34]. In the future high-resolution cameras and faster processors, both at acceptable prices, will tend to replace many, if not most, of the manual measurements now made and will probably make 100% inspection economically feasible.

2. Machine Vision for Tool Wear Measurement

The measurement of tool wear is of great economic importance. A nonintrusive, noncontact method is desirable, and novel approaches to this end are being developed in the laboratory [36, 37]. In principle, if the tool shape is accessible to optical imaging its wear can be measured using a solid-state camera. In practice, it is often difficult to obtain a clear view of the image. There are cutting fluids and chips in the line of sight. It may be possible to use fiber optics to circumvent some of these problems. In any case, by increasing the sampling rate of inspection of critical dimensions on the machined product, monitoring of tool wear can be improved substantially.

B. Inspection-Qualitative and Semiquantitative

Machine vision for this group of inspection applications is aimed at emulating a person when he visually inspects a workpiece or assembly for qualitative and semiquantitative properties without the aid of measuring devices. The human, however, may be aided by optical devices for, say, magnification or demagnification of images, masking or windowing of part of an image, comparison of outlines, etc. Potential applications are enormously varied and one can make only a crude and incomplete classification.

In Figure 3 five major subgroups are identified. A sixth subgroup, which could properly be included in this group, "In Process Inspection," has been described previously under "Sensor-Controlled Manipulation".

The five subgroups for applications of machine vision to inspection are under the headings: label reading and registration; sorting; integrity and completeness; cosmetic and surface finish properties; safety and monitoring. In all these applications the sensory and interpretative system of choice consists of solid-state cameras, interfaced with microcomputers and specialized hardware where necessary. In many instances it is certainly possible to engineer a special-purpose contact or noncontact solution that may be less expensive; however, it would be much more difficult to modify or adapt to other, similar applications. The following discussion, therefore, will assume availability of the adaptable and easily reprogrammed camera systems.

1. Label Reading and Registration

Printed characters on labels or directly marked on bottles, cans, cartons, etc. can be "read" by existing optical character-recognition (OCR) devices, provided that the position and orientation of these products are constrained within narrow limits. Similarly, bar codes can be "read" by available bar code scanners, under similar constraints. It is often costly to orient and position the products, as the insignia may be randomly positioned on given surfaces. Relatively simple programs exist to locate the insignia and recognize it in printed or coded form, using camera systems with far greater latitude in accepting variations of position and orientation.

It is also feasible to inspect labels to ascertain that they are properly registered with respect to the container. This will require relatively crude mensuration by the camera system, readily executable with the available resolution.

2. Sorting

There are many sorting applications in manufacturing processes in which workpieces of several types that are packed in containers or randomly arranged on conveyors must be recognized and then manipulated in a desired manner. Such applications include the orderly packing of workpieces of a single type in the container, the selecting of a specific workpiece from a random mix, or the identification and counting of each type of workpiece for inventory purposes.

The techniques and requirements described under "Manipulation of Separated Workpieces on Conveyors" and "Bin Picking" apply equally to sorting operations. In essence, discriminating one workpiece type from another is similar to the problem of identifying each of the stable states for a single type of workpiece. Obviously, the system must be able to discriminate more stable states. The level of performance, therefore, depends on the number of stable states for each type. Satisfactory performance has been obtained on up to a half-dozen different workpiece types, each with several stable states [16].

3. Integrity and Completeness

This subclass of inspection is perhaps the most important and most essential of this group. It includes qualitative and semiquantitative inspection of individual workpieces for many types of flaws and errors incurred in fabrication and handling, including burrs, broken parts, pits, cracks, warping, defects in printed-circuit wiring, etc. The approximate size and location of key features, such as drilled holes, bosses, etc., can be measured for gross conformity to specification. Such inspection for the integrity of individual workpieces may be explicit, occuring after such fabrication processes as casting, machining, punching, bending, and drilling; inspection may also be implicit, performed as part of the assembly process itself.

Inspection for completeness is universally required to assure that subassemblies and assemblies have all the right parts present in the right places.

Each type of defect requires the development of a specialized computer program that makes use of a library of subroutines, each accomplishing the extraction and measurement of key feature. In due course this library will be quite large and able to cope with many common defects found in practice. Simple vision routines utilizing two-dimensional binary information, as previously noted, can handle a large number of defects. However, three-dimensional information, including color and gray scale, will ultimately be important for more difficult cases.

Inspection for completeness is usually difficult and, to be effective, will probably necessitate the use of structured light and three-dimensional information. Such inspection techniques have barely begun to be developed in various laboratories.

4. Cosmetic and Surface Finish Properties

Stains, smears, color, blemishes, dirt, tears, discontinuties, and the like are all defects found on the surfaces of many finished goods. These defects are usually cosmetic rather than functional, are esthetically unacceptable, and have an adverse effect on the marketability of the product. Some representative examples are:

- Discernible variations in paint finishes on car bodies and major consumer appliances.
- Discontinuities in polished ceramic surfaces and on polymer sheets.
- Oil, stains, dirt, and superfluous marks on toiletries, paper, cloth, cartons, etc.
- Torn and crushed wrappers of cosmetic and food packages.
- Ripeness (by color), rot, scabs, and other blemishes on fruit.

Many of these defects can be detected with the camera systems, utilizing two-dimensional information only. In almost all cases, however, specialized incident lighting must be engineered with an appropriate selection of spectral band, filters, and direction(s) of incident light relative to the inspected object. Here too each application requires a specialized computer program tailored to the job, making use of library of common subroutines that extract feature information.

5. Safety and Monitoring

Safety and monitoring functions of machine vision are included for completeness. Modern robot arms moving at high speed with powerful motive forces can be very dangerous to human workers, as well as destructive to workpieces and other machinery. A highly desirable machine vision system--unfortunately very difficult to implement--could monitor the space surrounding the robot, and arrest motion when collisions are imminent. Concurrently, new safety mechanisms to effect sufficiently rapid deceleration of the moving links would have to be incorporated in the robot design. A very sophisticated vision software system, operating with several remote cameras, would be required to differentiate between the known trajectories of one or more robots and workpieces, and potential intrusions into the workspace by humans. Furthermore, the system would have to detect wild trajectories resulting from malfunction of the robot [39,40].

Such a system, even if available today, would not be cost-effective. However, it may be possible to approach a compromise solution with the aid of internal and other sensory modalities.

IV CONCLUSIONS

Machine vision can be applied to a large proportion of tasks in batch production of durable goods. It can be used to automate sensor-controlled manipulation in material handling and assembly, and to automate visual inspection.

Present robots and machine vision techniques are already sufficiently advanced to permit their initial introduction into industrial plants on a pilot basis.

More sophisticated robots and vision systems are now being developed that give every promise of meeting cost and performance criteria acceptable to industry.

There appear to be no fundamental obstacles to the early development of adequate and cost-effective machine vision systems for the many types of applications described in the this paper. The initial stage in achieving practical deployment in plants and factories will require a period of from two to five years, during which transfer of the new technology to advanced development user groups would be effected. In the next stage, a pilot installation would be implemented, followed by actual production-line operation.

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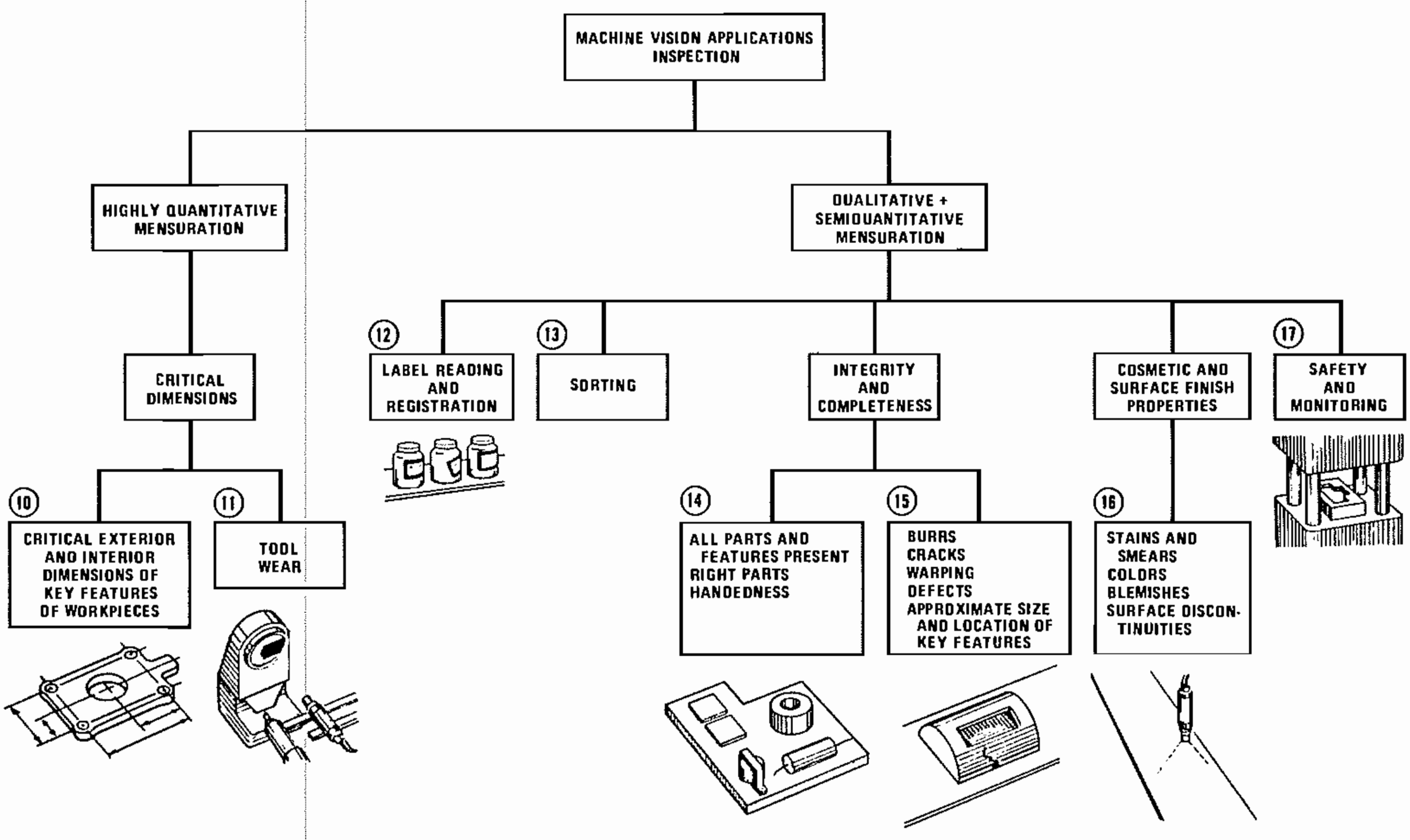
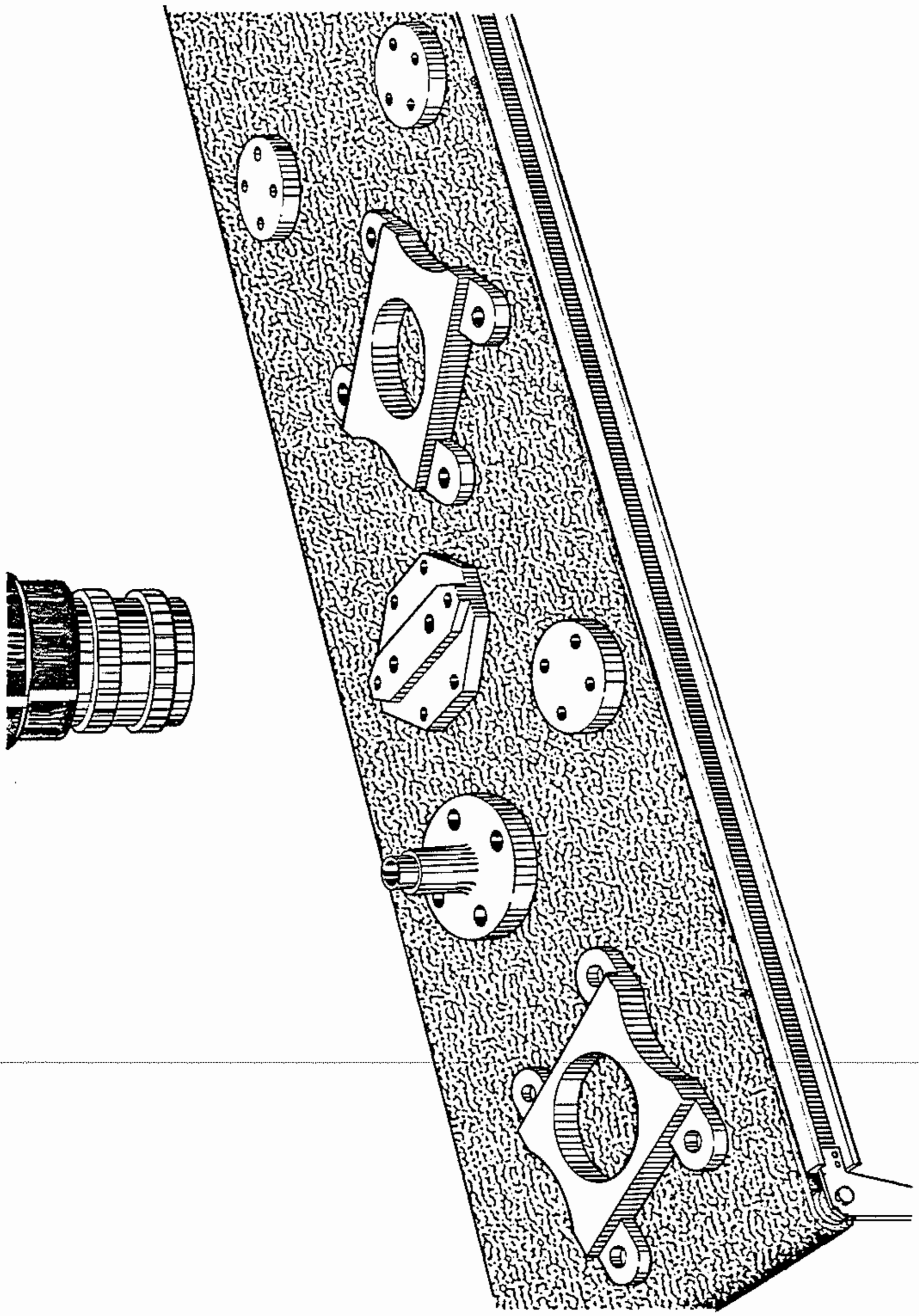
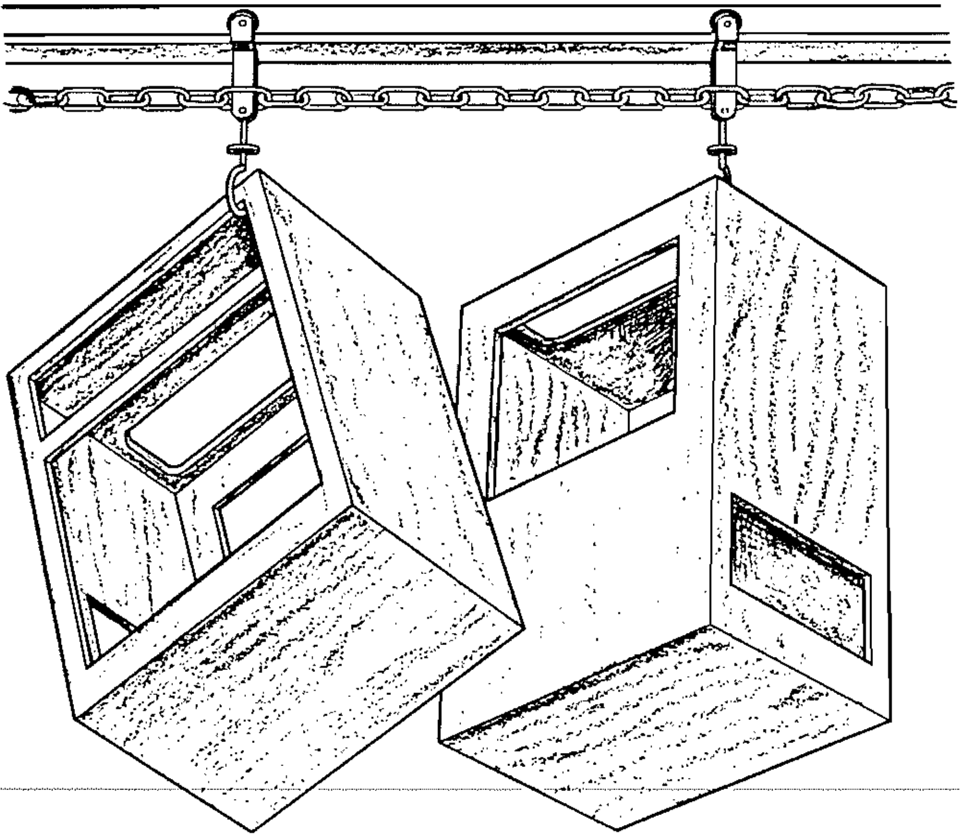
MACHINE VISION APPLICATIONS
INSPECTION





WORK LYING STABLY ON BELT

MANIPULATION OF PARTS PARTIALLY CONSTRAINED ON OVERHEAD CONVEYORS



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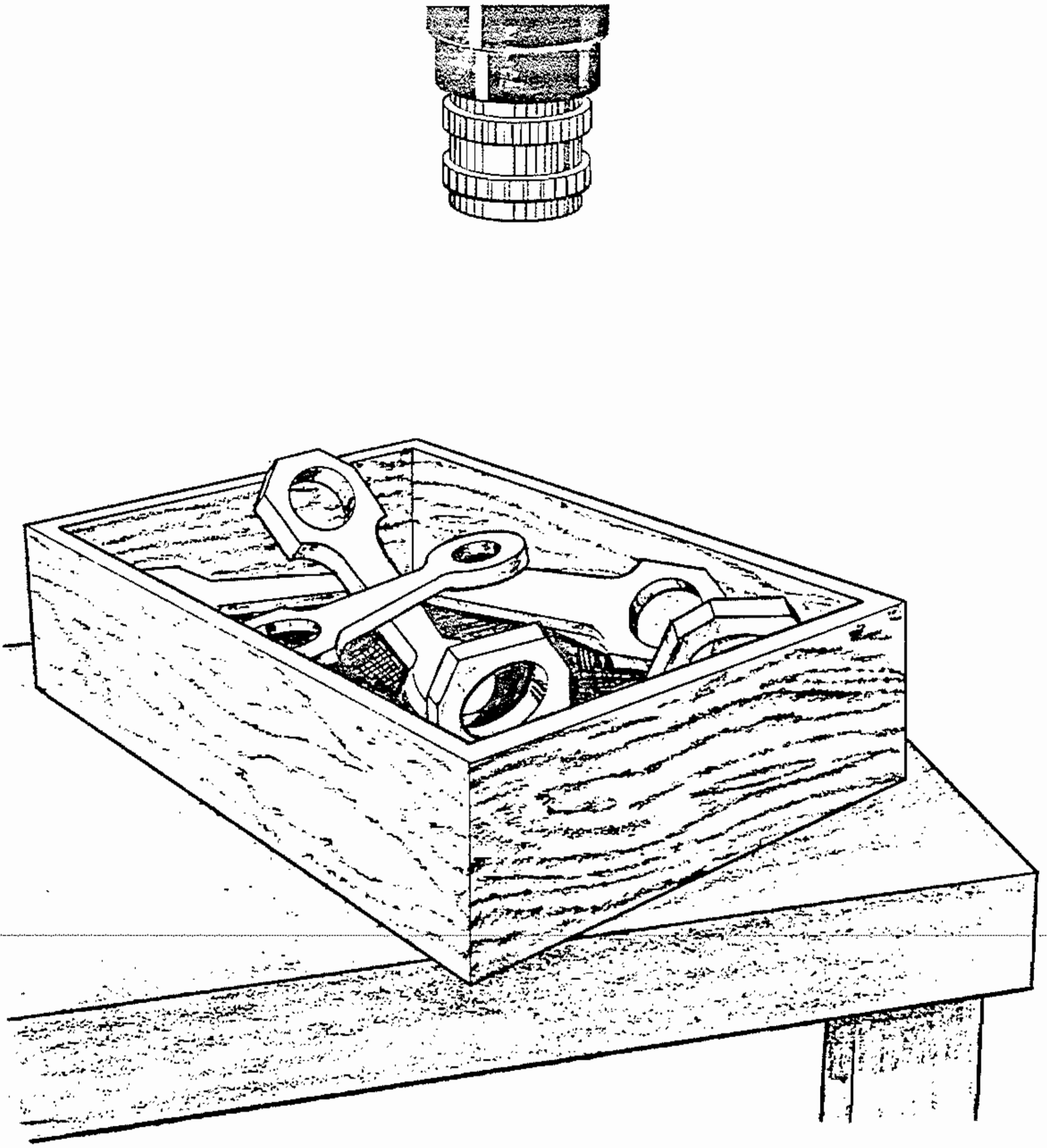
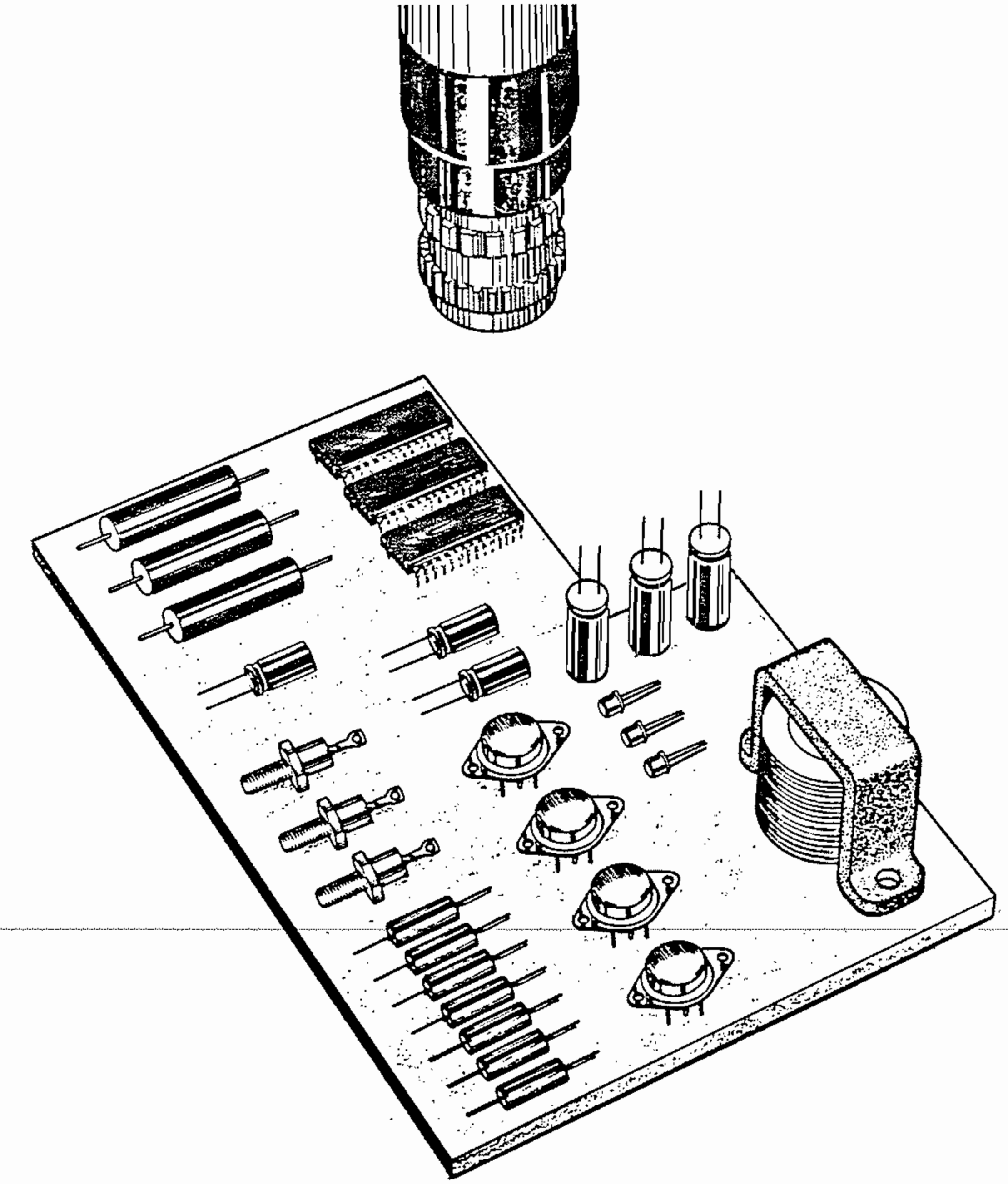
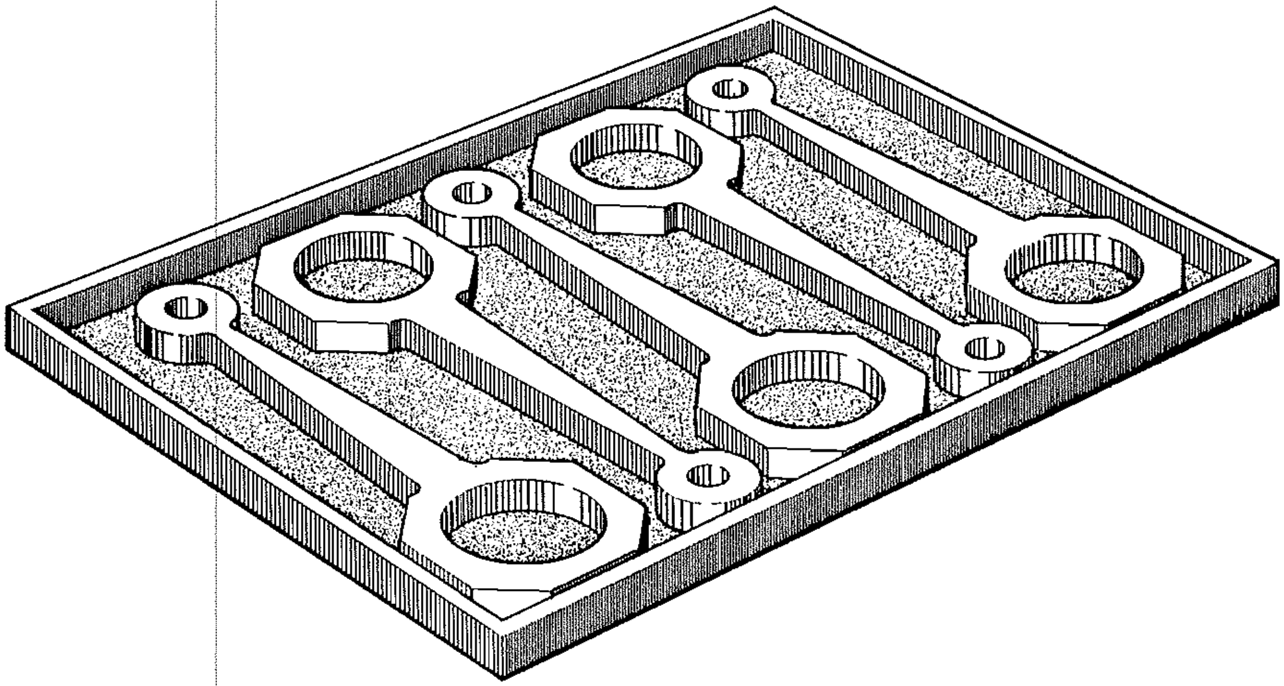


INSPECTION

INTEGRITY AND COMPLETENESS



BIN PICKING
PARTS PARTIALLY ORGANIZED SPATIALLY



MACHINE VISION APPLICATIONS
SENSOR CONTROLLED MANIPULATION