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# A study of machine vision systems :

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# A STUDY OF MACHINE VISION SYSTEMS: TECHNOLOGY, APPLICATIONS, PERFORMANCE, AND INTEGRATION

by

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# 1. ABSTRACT

Machine vision systems are being increasingly used in industry as the technology progresses and system cost decreases. Most current applications of the technology are in quality assurance areas. However, the application base is now expanding into other areas such as robotic guidance and process control. In addition, machine vision is being earmarked as one of the key technologies that will be needed to implement the automated "factory of the future."

This thesis examines a broad spectrum of topics related to machine vision technology and applications. The foundation of this thesis is a survey of the current technology and industrial applications of this technology. This survey reveals both the state of the art and the current constraints of the technology. However, the constraints are being quickly removed by current research which is also surveyed in this thesis. In addition, applications that will benefit from current research are also examined.

Machine vision systems are beginning to be integrated with other technologies at both low- and high-levels. Examples of this integration are in process control and robotic guidance. However, machine vision systems must be integrated into the overall factory structure so that complete computer-integrated manufacturing will be possible. This topic is reviewed, highlighting the needs that are pushing this integration.

One of the current constraints of this technology, (and other newer technologies), is the lack of industrial user knowledge. This subject is addressed by suggesting procedures for the analysis of system requirements, specification of those requirements, and for performance evaluation of completed systems. The thesis concludes with a brief review of the future of machine vision and recommendations for further study in this field.

## 2.INTRODUCTION

The recent surge in worldwide competition has forced many companies to take a long, hard look at themselves and evaluate what can be done to increase their own competitiveness in their respective marketplaces. Some of the responses from this type of introspection have been to concentrate on quality improvement, cost reduction, and productivity improvement. One of the newest technologies that addresses these issues is machine vision.

Machine vision has many other benefits such as improving worker safety and improving process control. In fact, many of machine vision's promises for productivity improvement are necessities for the concept of computer-integrated-manufacturing (CIM) to become a reality. If CIM is to become a reality, massive amounts of information from the manufacturing facility must be automatically integrated into the main computer system. This information must include process-related factors such as stock counts; identification, location, and orientation of work pieces; tool conditions; and the quality level of the manufacturing process.

To achieve this automatic gathering and transmission of data, machine vision can sense the many variables and events that occur in a manufacturing environment and communicate via networks to the main computer system.

Although machine vision systems hold many promises as being a vital link into the "factory of the future," problems in implementation still exist. Since it is a technology that just recently moved out of the laboratory, user education and acceptance have not fully been realized. In addition, the technology is changing and improving so rapidly, the user often finds it difficult to stay abreast. And finally, there exists a plethora of vision system vendors and systems. At the time of this writing, over 100 different vendors exist with over 100 different systems. These factors contribute to the evident need for corporations to become more knowledgeable in the following areas; machine vision technology, possible applications of vision systems, and the integration of machine vision into an overall manufacturing system.

## 2.1. THESIS OBJECTIVES

The purpose of this thesis is to review machine vision technology, and the application of that technology, to provide for a more efficient and effective implementation of machine vision systems in industry.

In Section 3, the review of machine vision technology begins by reviewing the technology itself and the benefits of applying the technology. Section 4, a literature review of applications of machine vision systems is conducted to form a framework that describes the current state of the art of applications of machine vision in industry.

The application review also identifies the current constraints of applied machine vision technology in Section 5. The constraints are identified and are classified by whether they are due to the technology itself or whether they are due to problems in applying the technology. However, a large amount of research is addressing the current constraints and is reviewed in the technology research section of this thesis, Section 6.

Section 7 is a review of the need for machine vision in the successful application of computer-integrated manufacturing. Machine vision integration at a process level and at a factory level is examined.

Due to the newness of this technology, user knowledge is lagging. This problem is addressed by reviewing the areas that must be analyzed to successfully specify and procure a vision system in Sections 8 through 10 of this thesis.

And finally, the thesis ends with a forecast of the future of machine vision and recommendations for further study in Section 11.

## 2.2. DEFINITION OF MACHINE VISION

Machine vision has been defined as the automatic acquisition and analysis of images to obtain desired data for use in controlling an activity.[1]

Machine vision is based on a four step process. The four steps are:

- * Image formation
- * Image analysis
- * Image interpretation
- * Communication

Each of these steps will be described in more detail in Section 3.

It is useful to first consider the functions of a machine vision system. The function is based on the type of information extracted during image analysis. The functions of machine vision systems are gaging, verification, flaw detection, identification, recognition, and location. These functions are reviewed in the following paragraphs.

Gaging via a vision system allows for non-contact measurement. This is beneficial where contact measurement would damage the part, slow down line speed, or be dangerous to man or equipment. Gaging by vision is faster and more reliable than human inspectors.

Verification consists of ensuring that an operation has been carried out successfully. The verification process has been used to ensure label placement and die or mold clearance status.

Flaw detection is a significant function of machine vision systems. Typically, a product flaw is detected solely by people, which prove to be unreliable in time. In machine vision, a flaw is considered an unwanted feature with an unknown shape at an unexpected position. This is an awkward definition, but reflects how a vision system operates. The vision system is trained to see all unwanted features, which are considered flaws.

Identification is the process of finding what an object is by reading symbols on that object. Typically, either optical character recognition or bar-code reading is used. This function has many applications in warehousing and production tracking.

Recognition is similar to identification, except that the machine vision system uses features of the object itself to determine its identity. The need for recognition is two-fold. Recognition is needed to identify one part from another and to recognize an object independent of its resting stable state. This is important in robotic applications.

Location is similar to recognition except that the part is known and only the exact location and orientation of the part has to be determined. This function has many applications in areas where the component is known, and the spatial relationships are to be found, such as in wire bonding applications.

## 2.3. APPLICATIONS AND BENEFITS OF MACHINE VISION

The following subsections will discuss the applications of and the benefits of machine vision. The number of individual applications are numerous but it is helpful to categorize them into eight broad classifications. The benefits of vision systems are also numerous but fall under two general categories.

### 2.3.1. APPLICATIONS OF MACHINE VISION

The eight categories of machine vision applications are: quality assurance, sorting, process control, material handling, robot guidance, test and calibration, machine monitoring, and safety. A brief description of these applications follows.

Quality assurance is simply the removal of defective product from a manufacturing process. This application is very important since costs and speeds of processes are increasing, requiring that defective product be removed quickly and efficiently.

Sorting by machine vision consists of separating product by observable characteristics. The demand for matched sets of product and levels of product quality will continue to make sorting a required process.

Process control via vision is used to provide data at high speeds to a manufacturing process to correct and control the equipment parameters to keep the operation within allowable tolerances.

Material handling is facilitated by vision systems. Vision systems can identify parts coming out of a warehouse or going in. This allows for the removal of people, providing for higher density storage and allows for degradation of the environment without concern for the effect on people.

Robotic guidance via vision is presently expensive and limited but is of major importance. Robots that need visual feedback are in applications such as assembly and continuous welding. Improvements and subsequent cost reductions will allow for vision to become an integral part of more robotic applications.

Test and calibration applications are becoming increasingly popular. In these applications, a mechanical device activates an assembly, say a calculator, and a vision system checks if the appropriate response has been elicited. Calibration is done by setting the device after a vision system has verified the correct position of a pointer, such as in automobile speedometers.

Machine monitoring is concerned with protecting a machine and to prevent the production of defective product. Vision systems can ensure correct machine operation and shut down a process if it is uncontrollable.

Safety of workers can be enhanced by machine vision. Applications of a vision system for safety purposes may be shutting down a machine or a robot if a person is in the workarea. Many applications of this type have not yet been implemented.

### 2.3.2. BENEFITS OF MACHINE VISION

Many benefits can be derived from the use of machine vision in industry. The use of vision is becoming more attractive due to cost savings. Payback periods are decreasing and returns on investment increasing as vision system costs are decreasing and capabilities are increasing. The following list and subsequent explanation indicates some of the reasons for applying machine vision:

* Improved productivity
* Satisfaction of technical requirements
* Minimize scrap and rework
* Improve process control
* Minimize equipment downtime

- Minimize product liability exposure
- Response to competitive pressure
- Improve worker safety
- Reduce employee turnover
- Reduce utility costs
- Reduce plant size

As is obvious, all of these reasons can contribute to cost savings and productivity increases.

Productivity improvement can be defined as more output per worker. By replacing workers with vision systems, productivity is increased due to less labor per product.

A new product or process may require a vision system to meet stringent technical requirements. Without a vision system for control, the new process may not be economically feasible.

Scrap and rework reduction is possible through the use of vision systems. Whether used for raw material or in-process inspection, machine vision screens out defective product reliably and quickly, thereby reducing scrap and rework.

Process control is enhanced with machine vision due to its ability to provide real-time process parameter feedback and its ability to gather process statistics for control.

Equipment downtime can be minimized by monitoring critical areas of machinery with a vision system, allowing the equipment to be shutdown before a minor problem turns into a major problem that causes breakage and excessive downtime.

Product liability exposure can be reduced by vision systems due to their reliability. The possibility of critically defective product being shipped to a customer is almost eliminated by a machine vision system.

New competitive pressures are responsible for bringing vision to the marketplace and will continue to force corporations to use vision to produce the best product at the lowest cost possible.

Worker safety can be enhanced by a vision system. Whether an environment is unacceptable to human entry or a close machine-human interface is required, vision systems can protect employees.

Employee turnover in tedious and repetitive jobs can be

<u>reduced</u> by implementing vision systems to perform those tasks. However, employees should understand that the undesirable jobs should be replaced by this type of automation so that the equipment is accepted by employees.

<u>Utility costs can be reduced</u> because automated equipment does not need the environmental quality that workers require.

And finally, <u>plant size can be reduced</u> because automated equipment does not require aisle space and areas to move around as people do. However, relatively easy access to equipment by maintenance personnel should be provided as well as safety precautions to ensure a hazard free environment for the worker.

This list is not complete and many other benefits exist but are not as tangible. For example, customer goodwill is probably enhanced due to the appearance of a well running automated production area that is facilitated by vision systems. Benefits will continue to evolve in this field as the technology and applications base expands in the future.

## 3. VISION SYSTEM TECHNOLOGY

The following sections of this paper will review the basics of vision system components and their functions. The topics will consist of lighting, lighting techniques, image formulation, image analysis, image interpretation, and communication.

### 3.1. LIGHTING

One of the most critical components of a vision system is the lighting used to illuminate the object that is to be analyzed. The goal of the lighting source is to illuminate the scene in a way to reduce the complexity of the resulting image, while at the same time enhancing the details needed for inspection and processing. The type of lighting source used, along with the lighting technique, (which will be reviewed in the next section), is very dependent on the shape and the optical characteristics of the part. Also, the background in the scene is important in that it allows for the proper contrast between the part and the background.

Typically, ambient or arbitrary light is not controlled enough to provide the proper illumination for an object. Ambient light changes in intensity and/or color can be catastrophic to threshold values, especially in binary systems. In addition, ambient light usually results in low-contrast images, shadows, unnecessary details, and specular reflections.[2]

### 3.1.1. PROPERTIES OF LIGHT

In forming an image, light energy, as it strikes a surface can be either absorbed, transmitted, or reflected, or some combination of these three processes. This response is dependent on the properties of the material. The wavelength or color of the light also affects the amount of light that is transmitted, reflected, or absorbed.

Reflection of light from an object is dependent on the surface finish of a material. If a surface is polished, such as a mirror, specular reflection occurs. Specular reflection is defined as light that is reflected at the same angle as the incident angle of the light. If a surface is dull or rough, incident light is scattered, which is defined as diffuse reflection. Both of these characteristics are utilized in the illumination of scenes to produce the best image. These characteristics can be adjusted by varying the angles between the part and the light source and between the part and the camera.

### 3.1.2. LIGHTING SOURCES

The most widely used light source is the incandescent lamp. In general, these lamps are the least expensive and the most readily available. Incandescent lamps create a broad spectrum of light, which is useful in most applications. However, this broad spectrum of light also includes infrared light, and this may have some detrimental effects on a vision system. Infrared light energy contains heat, which may affect the part being imaged or may affect the vision system itself. Also, a hot light source can be a hazard to employees.

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A drawback of a regular incandescent bulb is the declining light output over the bulb's life. Also, these lamps have limited lifetimes. The loss of the light output over time is due to the filament evaporating and recondensing on the cool glass bulb. In response to this problem, halogen bulbs were developed to minimize this effect. The gas, usually iodine, is pressurized into a small bulb containing the filament. This gas causes the tungsten to recondense on the filament, rather than on the bulb. The lifetime of a halogen bulb can be increased by operating below the voltage rating of the lamp. Near the operating voltage of the lamp, the increase in lifetime is inversely proportional to the twelfth power of the percentage decrease in voltage, while the light output decreases as only the 3.6th power.

Fluorescent illumination is useful when large area diffuse illumination is required. These lamps are readily available in many shapes, and special shapes can also be made if needed.

The light output of a fluorescent lamp pulses at twice the power line frequency. At a power line frequency of 60Hz, the lamp pulses at 120Hz. Even though the human eye cannot perceive this pulsing, it can cause a problem if the camera is not operating synchronously with the line frequency. If the camera is not at line frequency, the fluorescent bulb must be operated at a higher frequency, such as 400Hz, where the phosphor decay is adequately long to produce a relatively steady light output.

The type of phosphor used in a lamp changes the spectral peaks of the light within the visible spectrum. Therefore, it is necessary that all bulbs in a system, and all replacement bulbs, be made using the same phosphor. Additionally, the light output of a fluorescent lamp decreases over time, which must be considered in the application.

Strobe lamps are utilized when the application requires the imaging of a rapidly moving object. A strobe emits an intense burst of light, usually for less than 1/1000ths of a second, when a high power pulse is applied. The strobe must be synchronized with the camera, such that the short term storage of the camera can retain the image long enough for it to be scanned.

Relative to incandescent and fluorescent lighting, strobe lamps are expensive and less reliable over the long term. Also, strobe lamps in a manned production environment can be annoying and even dangerous to humans exposed to them.

Lasers are being used in machine vision systems when only a small area is to be illuminated. Because of the strength of laser light and energy, only low power lasers can be used. The principle advantages of a laser are that they are one color (monochromatic), and the light beam approximates a point light source, which allows a high energy density to be concentrated in a small area.

Fiber optic bundles are often used to carry light from a source to a location which is usually inaccessible by direct lighting. Typically, a quartz halogen light source with a reflector is used. Fiber optic bundles are available in many configurations, and can be custom made to fit almost any application. Also, a number of branches of bundles can be driven off of a single light source. Structuring of light is simplified by using fiber optic bundles.

Some special applications require the use of an ultra-violet light source. The principle use has been where two dissimilar materials appear in the scene. The materials are dissimilar in the sense that one of the materials fluoresces, and the other does not. When a material fluoresces, it emits light at a longer wavelength, and thereby provides a good contrast with non-fluorescing materials. An example of its use would be to detect the presence of grease on a metal part.[3]

The use of X-ray fluoroscopic imaging has been used to detect internal flaws in a part. The use of X-rays has been limited to such applications because of its complexity and cost. As with lasers, X-ray equipment must be checked often to ensure that radiation levels are below dangerous levels.

An application noted in the literature was for the inspection of already filled glass food jars for glass fragments or splinters.[4] Also, X-ray technology has been used in the inspection of surface mounted components on a printed circuit board for solder joint integrity.

## 3.2. LIGHTING TECHNIQUES

There are basically two methods for illuminating an object; back and front lighting. In addition, regardless of whether back or front lighting is used, the light between the source, the camera, and the object can be structured to acquire the desired contrast or effect. After the following discussion on lighting techniques, structured lighting will be reviewed.

### 3.2.1. BACK LIGHTING

Back lighting can be simply defined as the placement of the object between the light source and the camera. In most cases, a translucent diffuser is placed between the light source and the object. This is done to provide a uniform background to be able to silhouette an opaque object and to provide a high contrast image.

In back lighting, the light reaches the camera without reflecting off of the object. This provides only silhouette information, however, this enhances the process because it eliminates the extraneous information from the object's surface and provides good image contrast.

Back lighting is also used to examine transparent and translucent objects. This is possible because the object appears clear in the image except for at the object's edges and at any defects that are present. In these areas, some of the light is diffracted away from the camera and causes these areas to appear darker in the image.

Typical applications for back lighting systems are for presence/absence detection and non-contact measurement. Because of the silhouette that is produced, back lighting works well with both binary and gray-scale machine vision systems.

The use of a diffuser in back lighting causes much of the light energy to be lost due to the diffuser. A way of overcoming this, if necessary, is to replace the diffuser with a condenser lens. The condenser lens collects the light energy and focuses it on the camera lens. As with a diffuser, the condenser lens must fill the camera's view. Condensing lenses are limited in size, while a diffuser can be made to almost any size.

Back lighting can also be accomplished with the use of collimated light. This collimated light greatly reduces variations in magnification due to changes in object distance. Collimated light contains only parallel rays, and therefore the object appears as if it was at infinity. The effective magnification of the lens then determines an object's apparent size. A collimated light source can be constructed by placing an illuminated pinhole at the focal point of a collimating lens behind an object. Again, the light beam must be as large as the camera lens, and the object smaller than the camera lens.

### 3.2.2. FRONT LIGHTING

Front lighting is defined as where the light reaches the camera lens only after it has been reflected off of the object or the background. The use of front lighting allows surface features to be viewed. However, front lighting produces a lower contrast image than back lighting, and may also illuminate areas that are unwanted and may complicate analysis. Also, in front lighting, only a fraction of the initial light is reflected into the camera lens, requiring more light than back lighted scenes.

The reflectance properties of the surface are important in front lighting. The reflectance of the surface, whether specular and/or diffuse, will dictate the type of light source to be used. In other words, the choice of diffuse or specular front lighting will depend on the requirements of the desired effects.

To generate specular reflection off of an object, the angle of light incidence on the object must equal the angle of reflection from the object to the camera lens. Less light energy is required because more of the light is reflected into the camera lens. This type of illumination system is heavily dependent on part orientation because changes in the surface angle will greatly affect the amount of light reflected.

Diffuse reflection is accomplished by placing the light source such that specular reflection is eliminated. Typically, the illumination angles are best determined empirically, but are usually close to 45 degrees from the axis of the camera to the surface.

Since specular reflections greatly overpower diffuse reflections in the image, a diffuse illumination system must be designed to eliminate the possibilities of specular reflection. One method of accomplishing this is by enlarging the light source emitting area, which will reduce the relative intensity of specular reflection without reducing the diffuse reflection intensity. However, if image analysis is dependent on shadows, increasing the light source area may be counterproductive.

Front lighting applications include feature presence/absence detection, character or pattern recognition, non-contact measurement, and surface feature/flaw detection.[3]

### 3.2.3. ENHANCED AND STRUCTURED LIGHTING

Lighting can be enhanced or structured by many techniques that affect the light path between the source, object, and camera. These techniques include filtering, polarizing, lensing, and aperturing.[5]

Filtering is often put on light sources to remove unwanted light frequencies. For example, an infrared filter may be required for incandescent lamps to eliminate excess camera noise. Also, strobe lamps usually require blue filters to be effective.

Polarizing of light provides for better light intensity contrast for vision systems utilizing front lighting. Typically, a polarizer is placed in front of the light source and an analyzer is located in front of the camera. When properly adjusted, this polarizing system can eliminate unwanted glare, minimize unwanted diffuse reflections, and can improve the contrast in many applications.[6]

Structured light may also consist of the addition of lenses or apertures to the light source. This is done to shape the light into a pattern as it strikes the object. The curvature of the object distorts the light pattern. This distortion is then detected and is used to determine the curvature of the object.

## 3.3. IMAGE FORMATION

Once a scene is properly illuminated, the image must be projected through a lens into a camera, and then onto a photosite. A discussion on lenses is beyond the scope of this paper, but a few points that highlight the importance of lenses to a vision system will be made.

A lens must be well suited for the vision system application. The key variables in lens selection are magnification, object distance, and focal length. Aberrations in lenses do not allow for a perfect image to be formed. Aberrations are caused by physical limitations, design compromises, and/or manufacturing tolerances. Lenses must be designed or selected that minimize the effect of chromatic and spherical aberrations, and reduce the amount of pincushion and barrel distortion.

There are three general classes of image sensors utilized in machine vision cameras. These are the image pickup tube, the solid-state image sensor, and the laser scanner. Each will be briefly discussed.

### 3.3.1. TUBE-BASED CAMERAS

Image pickup tubes, such as the vidicon tube, utilize a photoconductive target of antimony trisulphide as the image sensing element. As light falls on the target, the impinging light energy causes the sensor to change from an insulator to a conductor, depending on the intensity of the light. Meanwhile, an electron beam focused at a point scans the back of the target for dark and light regions, and produces a corresponding electrical signal. Other forms of image tubes are newvicon, saticon, and silicon target vidicon. These operate on the same principles, but have improved target materials for better performance.

Most closed-circuit and broadcast television cameras utilize image pick-up tubes, which presents several advantages due to conformance to industry standards. This allows a standard aspect ratio for the image format, an industry standard output signal, and interchangeable "C" mount lenses can be used. Other advantages are low cost and high availability. Some disadvantages that image pickup tubes have are; susceptibility to damage by shock or vibration, possible sensitivity loss due to photosite burn, and susceptibility to geometric and sensitivity drifts due to changes in voltage, temperature, and aging of circuitry. External electrical and magnetic fields can cause geometric drifts also. Vidicon tubes also suffer from image burn, slow response time, and non-linearity.

### 3.3.2. SOLID-STATE CAMERAS

Solid-state image sensors use semi-conductors to convert light energy into electrical energy. The electrical energy is proportionate to the amount of light falling upon the sensor. The image sensor is made in an array of discrete photosensors. Each photosensor is on precise centers which assures linearity, and carries its own charge. There are three types of on-chip scanning devices which are MOS switches, Charge-Coupled-Devices(CCD), and Charge-Injection-Devices(CID).

CCD imagers utilize either full-frame or interline transfer devices. The full-frame device has a contiguous surface for collection of photon data and uses an interlaced mode of analysis such as in TV video. The interline approach weaves storage and transfer devices on the chip and presents some obscuration in the image. MOS and CID devices utilize sequential analysis which facilitates high speed processing.

Cameras using solid-state image sensors do not have most of the drawbacks of vidicon cameras such as geometric drift and aging. However, solid-state cameras suffer from the lack of standardization in terms of availability and replacement and also suffer from some degree of blooming. In addition, solid-state cameras are more expensive than cameras utilizing image pickup tubes.

### 3.3.3. LASER SCANNERS

Laser scanners use a single sensor that can sense both the light from the entire scene and the variation in reflected light. This scanning takes place in the object plane, rather than in the image plane as with solid-state and pickup tube systems. Laser scanners are used when very high resolution is needed. However, laser scanners are expensive and large, and have to be built to order. In addition, there is no standardization of laser scanners, and they must be periodically maintained to achieve peak performance.

### 3.3.4. ARRAY CONFIGURATION

A more important subclassification of solid-state cameras is by the size and shape of the photosite. The two major arrangements of sensing elements are matrix and line-scan. A line scan array is a single row of sensing elements while a matrix array is a two-dimensional array in a square or rectangular grid. Line-scan arrays range from 64 to 2048 sensing elements while matrix arrays range from 32x32 up to 360x488. Development work for fabricating larger arrays for better resolution is ongoing, but the speed of image processing must also increase accordingly to facilitate the use of larger arrays.

Additionally, a line-scan array, a one dimensional sensor, can be arranged in a circular format. These scanning devices have been applied for use in angular position measurement and in surface inspection of bore and cylinder diameters.[7]

## 3.4. IMAGE ANALYSIS

The process of image analysis contains various stages of signal and information processing. These stages include data conversion, formatting, preprocessing, segmentation, and feature extraction. These areas will be briefly discussed, preceded by a review of spatial and gray-scale resolution.

### 3.4.1. RESOLUTION

There are two types of resolution in a machine vision system; spatial and gray-scale. The spatial resolution of a system relates to the smallest detail discernible in a given field of view. The two factors that determine the overall spatial resolution of a system are the camera resolution and the image digitizer and buffer resolution.

Camera resolution relates to factors such as the size of the scanning beam in a vidicon camera and to the number of picture elements in a solid-state camera. The digitizer and buffer resolution is determined by the sampling rate and density, respectively. However, most cases require that features that are to be detected must be larger than one pixel for reliable analysis.

Gray scale resolution is calculated by the largest number of separate gray levels assigned by the video analog to digital converter to each pixel. A gray level represents the measured brightness of an image. Typically, vision systems can resolve from 16 to 256 shades of gray, with 64 levels being adequate for most applications that require gray scale processing. However, applications cannot depend on discerning only one shade of gray difference. Usually, a minimum of 15% change in shading is required for reliable results.[3]

### 3.4.2. DATA CONVERSION AND FORMATTING

Data conversion of the video signal into a form that can interface with a computer is accomplished by an analog to digital converter. Each pixel is converted into an output of a byte, which contains 4, 6, 8, or more bits of information. (Some systems compare an analog signal to an analog value and a binary output results, but these systems are not as common as the analog to digital systems.)

There are three common methods of formatting image data; the gray scale image, the binary bit-mapped image, and the binary run-length encoded image.

Gray scale image formatting and storage is relatively straightforward. Each pixel in the image is stored as a number in memory. Since each pixel is stored, the time required to access and store increases dramatically as the size of the image increases. Typically, systems that use gray scale images have additional hardware that can process gray scale images without overloading the central processing unit.

The binary bit-mapped image formatting technique converts gray scale data into binary data. The brightness of each pixel is compared to a preset threshold value, and then labeled as either light or dark. This reduces memory and processing requirements by one-eighth in an eight bit system, since each byte now can handle eight pixels of information.

An extension of the binary bit-mapped image is called the binary run-length encoded image. Each scan line contains only two main pieces of information; the locations where the image changes from light to dark and vice versa, and the distance between each of those transitions. Therefore, only that data is processed and stored, greatly reducing the amount of information a system must handle. However, the amount of data compaction depends on image detail, with ten times reduction in data amounts being typical.

Special memory arrangements have been formulated to facilitate high video data rates, since previous memory arrangements did not allow an image to be acquired while another was being processed. One such special memory arrangement consists of two complementary memories. While one memory acquires an image, the other memory is processing a previously received image. Another memory arrangement uses byte wide processing in a bit plane by utilizing a clocked shift register.

### 3.4.3. IMAGE PREPROCESSING

Image preprocessing is used to make images easier to analyze. The purpose of preprocessing is to either simplify the image itself or to gain some information about the image which will make subsequent processing easier. Image preprocessing is usually performed on gray scale images, which may be converted to binary images during the preprocessing step. Preprocessing can occur on incoming images or on images retrieved from storage.

An intensity histogram is a common preprocessing tool. The histogram consists of a plot that identifies the number of times each gray level appears in an image. This can be used to determine whether an object is present, so the system does not process information from an empty scene. An intensity histogram can also be used to determine a threshold level. A bimodal histogram resulting from a scene can be converted into a binary image, using the trough between the peaks as the threshold level. Also, the effects of illumination level and surface reflectance changes can be seen from the threshold level changes and then be altered accordingly.

The point transformation process, a global operator, can be used to replace gray scale values with new values. Point transformation techniques often use look-up tables for processing. This method is used to improve contrast in an image, correct for non-linearity, and gray scale to binary transformation.

Non-uniformity caused by non-constant illumination or by lens border distortion can be corrected by using offset and scaling factors. These factors can be in the hard memory or can be recalibrated periodically and reread into random access memory.

Images can be subtracted from reference images to determine the difference between the current image and the standard. This is a form of template matching that utilizes an intensity histogram on the subtracted image result to detect the magnitude of change.

Convolution, another preprocessing technique, uses filters and edge detectors to gather information about a scene. However, convolution is a very computationally intensive process. A two dimensional array of numbers called a kernel is used over a matching group of pixels in an image, the values are summed, and the new value is written into a new image at the center of the kernel. This is repeated at other locations until the new image is filled.

The convolution technique can be used for both high- and low-pass filters. In addition, edge detection is accomplished via the convolution technique using either the Roberts or the Sobel operators. These operators are based on calculating intensity gradients for pixels in the original image and identifying local rapid changes as edges.

Neighborhood operators, which contain convolution techniques as a subset, operate on a local region in an image. These operators can be linear or non-linear, convolution being a linear operator. Non-linear operators are used to manipulate shape and size of an object in an image. Operators such as dilation and erosion are combined with linear operators such as subtraction to generate information from an image without other complex operations. These techniques have successfully been used to inspect gears for through hole size and missing teeth.[8]

### 3.4.4. IMAGE SEGMENTATION

Image segmentation is also used to simplify analysis by transforming a scene with a number of objects into simplified one object images by eliminating unnecessary features from an image.

Intensity thresholding can be used to separate object images if salient features differ in intensity. Repeated applications of these window thresholds at different levels can be used to separate an object from its background. However, a disadvantage of this process is that edge pixels may be erroneously categorized by intensity thresholding.

Windowing also segments an image. However, with windowing, no transformations take place and no new images are generated. Windowing only treats a subarea as a separate image. By using multiple windows on one image, multiple objects can be segmented.

A segmentation algorithm named connectivity analysis has been developed at SRI International. Run-length encoded images are stored as lists that specify the horizontal coordinates of each transition between light and dark. The process then evaluates successive scans to check for overlap in regions in terms of transition segments. The analysis ultimately produces lists of segments that represent regions, however, the lists must be linked into sets that represent the object in the scene.

Another method of segmenting images is by a process called boundary tracing. Adjacent edge pixels are evaluated successively to identify where the image boundary lies. A clockwise or counterclockwise directional scheme is used until the trace returns to the starting pixel. The trace may then be stored as a list of discrete boundary point coordinates or a chain code of moves from one point to another.

### 3.4.5. FEATURE EXTRACTION

The last step of image analysis is feature extraction. Features are descriptors of the object in the image. These features are recognized and assigned a label or a name. From these labels or names comes the interpretation, or assignment of meaning, of the objects in the image.

One of the simplest methods of feature extraction is pixel counting. Pixel counting can be used to: find the area of an object; along with windowing can inspect part features; and can measure a dimension in a scene.

Measurement bars, which are imaginary lines placed across an object, can also be used to measure dimensions or features on the object. Some research is now being conducted to measure to sub-pixel accuracy. This is done by averaging the dimension to below pixel resolution by measuring the edge transition which occurs over a number of pixels. However, there are still problems with this technique, such as blurred edges and part position changes. Measurement bars can also be used to count edges in a scene, relating to the number of items in a certain region of a scene.[9]

Average gray levels can be computed in a window to verify the presence of objects in an assembly.

Template matching, as mentioned earlier, compares an image to a stored reference image. The number of pixels that agree or disagree quantify the relationship between the image and the reference image. However, the part must be located, or registered in the same orientation as the test image. If not, one of the images must be translated, usually in rotation, in order for the images to be compared. This is costly in terms of real time computations, so rotational misregistration should be avoided if time is a critical factor.

Another form of template matching is correlation.

Correlation only compares the test image to a subregion of the image. The procedure is repeated until the test image has been moved all over the scene, and a match score is computed for each move. If the score meets a minimum value, then the image has been identified, and the maximum score position identifies the location of the image.

As mentioned earlier, the connectivity analysis algorithm was developed by SRI International. From the analysis, various geometric characteristics can be extracted from the object. These include area, maximum and minimum width, height, perimeter, centroid position, orientation (from second moments), and elongation and compaction indices.[10]

Other features, or descriptors can be extracted to help the system classify or identify an object. These techniques can be classified as either depending on boundary or region information.

An example of a boundary technique is the Fourier descriptor, which record points along the boundary of the part. The resulting quantity, due to the nature of the Fourier transform, does not depend on the orientation of the part. Therefore, changes in size and rotation are only transforms in terms of multiplication by a scalar or an angle, respectively.

Regional techniques use, for example, topological information such as the Euler number. The Euler number is defined as the number of connected components in an image less the number of holes. Although it is a general descriptor, it does not depend on scale or rotational location. Other descriptors used are bounding box center coordinates, eigen-axes directions, vector directions to certain part attributes such as the most distant points.[2]

## 3.5. IMAGE INTERPRETATION

Image interpretation is closely linked to image or object recognition. Interpretation consists of assigning a meaning or making a decision on the objects that have been labeled.

The most common approach to decision making is the comparison of the image to what the system has been taught is a good image. This is done by teaching the system what a good part is. The system builds up a numerical model of what a good part is by its characteristics or descriptors. These descriptors are compared to the image's extracted descriptors and a decision is made.

When a vision system is used as a dimensional measuring device, acceptable measurements are stored in memory. The system then takes measurements on the image and compares them to acceptable measurements and makes a decision. Calibration of a system is sometimes done by showing it a gage or a standard part.

As discussed earlier, correlation and template matching are techniques that are used to compare objects to a reference standard. This comparison, usually done by pixel scoring, also serves as an interpretation device. The match score is used to make a decision about the fit of the image to the standard. This interpretation technique is used in part presence verification or testing of selected parameters against acceptable limits.[11]

## 3.6. VISION SYSTEM OUTPUT

There are three basic categories of outputs of machine vision systems. The first type is the output of information and/or video signal for informational purposes only to other equipment or people. The second classification of outputs are those used to control mechanical equipment at a low level. And finally, the last

# RETAKE

The Operator has
Determined that the
Previous Frame is
Unacceptable and Has
Refilmed the Page
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### 3.6.1. INFORMATION AND VIDEO OUTPUT

The first group of outputs is for informational purposes only. It is useful to think of the three categories as increasing in complexity and power. The information only output is the simplest and does not provide any control functions.

The outputs in this classification may consist of a message on a monitor, a video image, or the loading of information into a computer for recordkeeping or statistical analysis.

A message output, usually intended for use by people, can serve many functions. A process running under the supervision of a vision system can provide constant feedback to operators on the status of the process. Examples of this type of output are many. A few samples are as follows;

- *Status of process; up, down, no parts, etc.
- *Diagnostics; reason why process is down
- *Measurement; dimensions being produced by process
- *Conditions; tool wear, clearance

An output of a video image is for use by people only. Typically, the image is a real time video image, rather than a digital image, used to indicate to an operator the general status of a process. The image can indicate whether parts are present, whether the process is running, and whether any other gross malfunction exists. Some preprocessing techniques may be applied to the original analog image to enhance critical areas for the benefit of improved perception by the operator. The image presented to the operator would be a digitized image, to allow the operator to see what the system is actually "seeing."

The last output under this category is concerned with loading process information into a computer for recordkeeping or for statistical analysis. The use of this output for recordkeeping is important in the food and drug industry in terms of keeping track of manufacturing lots. Outputs of test results such as measurements can be loaded into a computer to keep track of process efficiency. This is done by statistical analysis on the data. The analysis is usually done on a floating basis, such as by shift or daily. This serves an important function in production management.

### 3.6.2. BINARY CONTROL OUTPUT

This category of outputs for controlling mechanical equipment is usually in binary form, i.e., sending a signal that controls a device by an on or off output. The most popular application of vision, quality assurance, uses this type of output extensively. When a vision system is mounted on a machine or a process, its typical function is to measure the parts to ensure they are within allowable tolerances. The output of the vision system serves to open or close a reject gate, or to shut down the process when a number of defective parts are made consecutively, or both. This indicates the possibility of multiple binary outputs, which is commonplace.

Some process control applications utilize this type of output. Examples are the control of a paint sprayer, air jet activation, or welding control. Again, these devices are only given a binary signal for control.[12]

Although the outputs are being used to control equipment, similar information could be provided to operators to inform them of the status of control. An example would be the message output to an operator when a part is rejected. Additional information could be given such as the amount of dimensional non-conformance so that the operator can recognize a trend in the data. However, the recognition of trends can be performed statistically by a computer, and the results fed back to the operator, while still rejecting defective parts.

### 3.6.3. HIGH-LEVEL OUTPUT

High-level output is the most complicated and the most powerful of the three output categories. This consists of transferring information to other equipment or people. Perhaps the criteria that could be used to designate this type of output is the amount of reasoning or the level of intelligence the processor must have to complete the task.

Applications of this type of output are typically used for higher level process control and robotic control. In terms of process control, the output would be more complex than just a binary output. Typical examples of high-level output for process control have been implemented in axial component orientation for bandoliered product and for alignment of integrated circuit leads prior to bonding. Both of these applications require the vision processor to make a decision on the amount of correction needed to successfully complete the task. This amount of correction is then transformed into an output signal that contains the commands needed to bring the process into control.[13],[12]

Robotic applications typically require this type of complex reasoning and output for tasks such as guidance and obstacle avoidance. In simpler robotic guidance applications, the vision system is used for alignment by determining part centroids and axes in space, and providing that information to the robot so it can locate and grasp the part. This type of application requires minimal input to the vision system in terms of knowledge about the part. However, this reduces the ability of the robot to complete tasks of this nature due to the variation in the environment.

Current research in the field of model-based systems is studying the use of CAD design data for input to provide expectations of context for the robot/vision system. These systems will allow faster image processing and more complex outputs such as the confirmation of expectations, part recognition, and exact orientation. Further discussions of this research is presented in the technology research section of this paper.

This type of high-level output can also be provided to people also. Analysis performed by vision systems for tasks such as complex inspection can be outputted on a CRT for engineering analysis. Calculations of an object's characteristics such as its centroid or principle axis can assist an engineer in the analysis of a part's design. The use of this type of output for analysis will increase as more intelligence is implemented in vision system software.

## 3.7. PART PRESENTATION

The method in which a part is presented to a vision system is very critical. The tolerances, or variation in the location of the part will add to the precision degradation of the system. Overall system precision will be covered in the next section.

Fixturing, or staging must be more precise for objects that are smaller than the optical field of view of the system. Vision inspection of parts with tolerances less than +/-0.3mm require critical staging or registration correction software.

Many different approaches are used to present parts to a vision system. Three general categories of presentation systems are; precise registration for viewing that is within the accuracy requirements of the process, approximate registration such that only fine alignment by the system is required, and random registration such that the system must find the part location and orientation. As is obvious, part presentation is only critical in the first two categories. The random registration of parts, such as a jumbled bin of parts, requires no special presentation techniques.

Parts that must be precisely registered use material handling devices such as x-y-z tables, vibration free drives, and hand loaded fixtures. Since the vision system does not correct any misregistration, these devices must be accurately made and effects of wear over the long term minimized.

Presentation systems that locate parts to an approximate location require less precision in design and build. Conveyor belts and robots are used to present the parts in an approximate fashion for analysis by the vision system.

Software techniques such as two axes registration windowing are used to locate the part and to adjust the inspection window. This technique is often used when a vision system is retrofitted on an existing processing line.[14]

## 3.8. SYSTEM PRECISION

The ultimate goal of a vision system is accuracy, while the primary design goal is to ensure precision. This is because of the fact that once precision has been achieved, accuracy can be calibrated into the system. In terms of inspection, precision is defined as the repeatability of a system, while accuracy is defined as how close a measurement is to a standard.[15]

There are many factors that affect system precision or repeatability. Since each factor contributes to the non-repeatability of a vision system, an attempt must be made to minimize their effects. The following paragraphs will review these factors.

Mechanical effects of non-repeatability are caused by the staging mechanism. The staging mechanism itself, such as a position encoder driven by stepper motors, will have a resolution limit. This factor and others such as hysterisis, loose couplings, wear and others add to the mechanical non-repeatability of a system.

The basic digital resolution of a system is usually stated for a vision system. This is not the total system resolution or precision as is often misinterpreted. The effects of the optics, the camera, and the digitizing elements must all be considered, as well as the rest of the factors that affect precision.

Another broad class of factors that affect precision are environmental factors. These non-repeatability factors are caused by; temperature changes, vibration, dirt, alignment changes, lighting changes, and other factors such as electronic noise.

Many of these factors are application dependent. For example, an application that requires a measurement within the +/-0.3mm range does not require anything more than a solid camera to stage mount to isolate vibration, but any smaller tolerances would require additional preventative measures such as camera and stage air shock absorber isolation. In summary, all of these factors must be considered and estimated such that the precision of a vision system can be evaluated.

## 4. LITERATURE REVIEW OF APPLICATIONS OF MACHINE VISION SYSTEMS

The purpose of this section of the paper is to review the current state of the art of applied machine vision technology. The number of applications is tremendous, and only a few will be briefly reviewed here.

Machine vision systems can be classified by the type of application, or the end result or action of the vision system. Different functions may be performed by the system, but the end result can be classified by the following eight categories; quality assurance, sorting, process control, materials handling, robot guidance, test and calibration, machine monitoring, and safety.

According to the study done by Frost & Sullivan on the 1982 vision market, the proportion of applications were as follows, in terms of dollars: inspection and measurement-60%; part identification-30%; guidance and control-10%. It can be seen that quality assurance applications dominated the vision market.[11]

Additionally, a literature review will provide the groundwork for evaluating the current constraints of machine vision technology and the application of that technology. These topics are discussed in Section 5 of this thesis.

## 4.1. QUALITY ASSURANCE

As indicated in the previous section, the application class of quality assurance composes a majority of recent applications of machine vision. Therefore, the number of quality assurance applications reviewed here will be proportionately higher than the other categories of application.

Quality assurance is the removal of defective product from the manufacturing process. This can be done on-line, i.e. during or immediately after the manufacturing process, or off-line, outside of the manufacturing process. Quality assurance can be accomplished by measurement of dimensions, verification of feature presence or shape, or by the detection of flaws. Therefore, many different functions of machine vision systems can be used for a single application category such as quality assurance.

### 4.1.1. VERIFICATION

A quality assurance application of machine vision performing print verification provided some insights on financial evaluation of vision systems. The system checked the legibility of printed characters on dual in-line packages(DIPS) at the rate of 6000 parts per hour, or a character rate of 42 characters per second. The system rejected unacceptable parts prior to ink curing, which allowed for easier rework. Although the system is relatively straightforward and simple, it shows the financial benefit provided by vision systems. The initial system replaced six operators on one and a half shifts for a net present value of $273,103 and a payback of 0.18 years. The corporate tax rate and discount rate used were 50% and 20% respectively. This investment would easily be justifiable in almost any industry or economic climate.[16]

There have been many applications in the literature pertaining to the inspection of printed circuit boards. See, for example, [17] or [18]. These applications check for proper component presence and positioning, lead through the hole verification, board identification, and proper lead clinching. Typical inspection time for a complete board is one to four minutes, depending on size. Although these systems are quite an accomplishment in terms of technology, there is a need for more complex systems. New systems are needed for process control of component insertion, especially due to the increased use of surface mount components. This is due to the high cost and slow rate of repairs, once a defect has been found. This topic will be discussed further in the process control section.

### 4.1.2. FLAW DETECTION

The use of X-ray technology coupled with video cameras and microprocessors has lead to some successful applications that no longer require X-ray film, which is both expensive and time consuming. Vision systems can now provide almost real-time analysis using X-ray technology. Two applications of this technology used for quality assurance are for the automatic inspection of artillery fuses and for the automatic inspection of food jars for glass fragments.[19],[4]

### 4.1.3. GAGING AND ORIENTATION

Optical gaging or non-contact measurement is perhaps one of the most popular applications of vision systems. A fairly complex application of this technology was used to optically gage crankshafts. The system made and analyzed 10,000 individual measurements to monitor 54 characteristics for each crankshaft. The system compared the crankshaft to a standard or "golden" crankshaft by which it is calibrated weekly to minimize the effect of system drift. One of the most interesting aspects of this application is the amount of variation due to temperature changes. To compensate for this, the temperature of each crankshaft is measured by a sensor and scale factors are used to change the measured data to the standard to take into consideration the amount of expansion or contraction. The system has been found to be repeatable within 10% of the tolerance band width and accurate to within 5% of the known value.[20]

There have been a number of applications of robot-based vision gaging systems. The use of robots allows for maximum flexibility and the use of CAD/CAM database information to be calibrated into the part coordinate system via reference datum points and planes. However, variability in robot positioning adds to the non-repeatability of the overall measurement system. Applications of this type of system have been made in areas such as flexible tube and car body inspection with achieved accuracies of 0.05 to 0.2mm.[21]

A quality assurance application of a non-contact measuring system consisting of an x-y table with z axis measurement capabilities has been reported by Texas Instruments, Inc.[22] There were some novel ideas incorporated into the system. The system has z axis measurement capability by using an autofocus function. The autofocus function is based on the detection of surface texture and the optimization of transition counts from light to dark regions on the part surface. A histogram is constructed of the transition counts and the maximum height is related to the actual z height. The other novel idea used in the system is its ability to be downloaded with inspection data from a CAD/CAM system. The data is downloaded from a host in a custom version of the APT NC language through a compiler. This enhances the use of the same data base for design and manufacturing and allows the vision system to operate in an automated environment. Reported accuracy of the system is within 0.005mm, but system precision is only within 0.076mm due to table encoder and camera/optics resolution variation.

An example of multiple camera use with a single processor was provided by a quality assurance application in the watch industry. The four cameras were used to inspect a watch sub-assembly as it progresses through several stages of assembly. Inspection operations such as pin orientation and gear concentricity checks were performed. The multiplexing of cameras reduced the overall system cost while able to maintain the overall line speed and resolution requirements.[23]

## 4.2. SORTING

Sorting is the process of segregating parts by their characteristics or markings. In some cases, it is difficult to distinguish quality assurance applications from sorting applications because quality assurance is simply sorting by defect. However, other applications are clearly sorting by grade, tolerance, or type of defect.

An application in sorting chips after laser etching showed the financial benefit of vision systems. Chips are usually tested as to their tolerance ranges, and then are laser marked with a code, or left unmarked if they are completely out of specification. The characters are so small that 100X magnification was needed for an operator to read them. The operator then instructed a pick and place unit via keyboard entry to sort the chips into the proper bins. A vision system replaced the operator in the process and resulted in a payback of 0.53 years and a net present value of $75,728. The system was used three shifts a day and a 50% tax rate and a 20% discount rate were used.[16]

An interesting approach to the inspection of solder joints was presented by Besl, Delp, and Jain.[24] Other techniques for vision inspection have been solely for classifying a joint as good or bad. The approach cited was to classify a joint as being good or as bad, but the bad joints were also classified into a class of bad joints. The proposal consists of using gray scale analysis of the light intensities as a third variable to x and y dimensions. Rigorous mathematical analysis is used in the algorithm while extracting information from class and feature lists to classify the joint. This approach is motivated by the future goal to automatically take corrective action on the assembly line, which is highly dependent on the defect type.

There has been some research and primitive applications done on vision based feeder bowl systems. Two of the most interesting have been done by SRI and Phillips Research Laboratories.[25],[26] Both systems are trained by showing the correct part in acceptable orientations. The SRI "Eyebowl" uses two dimensional image sensing to identify the part in its correct orientation and to channel it to the correct chute via air jets and gates. Meanwhile, the Phillips bowl does not sort the parts, but allows the parts to only pass in the correct orientation. Both systems show a lot of promise due to their high level of flexibility and quick changeover and retraining time. Both systems can be configured to store image data in memory such that changeover to previously run parts is only a matter of data transmission to the system.

## 4.3. PROCESS CONTROL

Process control can be enhanced by vision systems. Measurements can be taken by a vision system and information fed back to the process in terms of processing parameters that must be changed to optimize the process. Process control seems to be one of the most complicated systems to implement in discrete part manufacturing, especially when the application becomes more complex.

As stated earlier, process control is almost becoming a necessity in component placement and soldering in the manufacture of printed circuit boards. Some steps are being taken to accomplish the task of vision feedback to control pick and place mechanisms that place components onto or into a board. However, complete closed loop systems are not yet available, but plans and architectures are being researched.

An example of a vision based process control system for component cut-off and insertion has been described by Asano, Maeda, and Murai.[27] The system uses two cameras to locate the leads of the component once they are cut to length, and this information is passed to the x-y table which automatically locates the board to the exact location for each lead. Typically, the leads are of two different lengths and the table is readjusted for each lead insertion. The advantage of this system is that mechanical lead guides are no longer required which allows for tighter packaging density and allows for variable pitched components. A similar system was seen at the Westinghouse Manufacturing Systems and Technology Center.[28]

As mentioned earlier, complete process control for printed circuit board assembly is the future goal. Several articles address this issue. See, for example, [29] or [30]. Most of this research is in the assembly of surface mount devices(SMDs) rather than in axial or radial leaded components. The use of SMDs is increasing due to their smaller size which allows higher packaging densities, less critical positioning requirements, and higher placement rates. Current technology allows for the machine vision inspection of completed boards, but repairs are still done manually. Repair costs are high due to the amount of labor required to complete the repair. There are different solutions that are presented to improve the reliability of the assembly process. These will be addressed in the section on integration of vision into manufacturing systems.

Other areas of applications of machine vision systems for process control have been cited in the literature. A machine vision system with a line scan camera was used to determine the edge points of varied size flat stock as it passed on a conveyor. Glue was to be applied around the edge of the stock. The vision system found points on the outline of the stock, fitted a line through the points via a least squares regression, and then signaled two servo motors to apply a continuous line of glue to the stock. The system proved to be very flexible, as various sizes and shapes of stock could be presented and no problems were encountered in the adhesive application process.[31]

The steel industry has been able to reduce crop shear waste by using a vision system to find the optimal cut location.

(Crop shear is the trimming of a hot steel slab to size and squareness.) The application of this system to a hot strip mill has yielded a monthly savings of $103,000, which relates to a payback period of three months.[32]

A foundry used a laser vision system to control the amount of molten iron poured into a mold, whereas previously, a 10% overpour was required to ensure that the mold would fill. This application paid for itself in four months.[3]

## 4.4. MATERIAL HANDLING

Machine vision can help material handling systems by properly identifying material by reading codes or characters on the material itself or on a container that holds the material. Warehousing systems and production lines that require the tracking of material will need machine vision systems to properly identify material for counting and routing purposes.

Many times, material handling vision systems are embedded in other systems. An example of this is in the auto industry in car body painting lines. A line scan camera identifies the type of car body on the line and instructs the robot paint sprayer to follow the appropriate pattern.

Other systems in the auto industry read vehicle identification numbers on the body which characterizes all the options that the car body must receive.[33]

The food and pharmaceutical industry has a great need to track their products in terms of lots and date codes. Most of their requirements were mandated by the Food and Drug Administration. However, many other companies in different industries have found it useful to be able to track and identify lots of material, all of which require machine vision. An example is in the semiconductor industry where attempts are being made to automate wafer production. This will require the need for each wafer to be identified by an 18 character alphanumeric code that has been adopted as a standard. Optical character recognition systems will be used to facilitate the tracking of wafers through the manufacturing and inspection processes.[1]

## 4.5. ROBOT GUIDANCE

There is an explosion of interest in the use of machine vision for providing information for adaptive control of a robot to ensure an accurate path or end location. There has been a great amount of research done on these vision robot systems as well as applications of this technology.

Some of the most current applications will be reviewed.

An interesting application of vision aided robotics was presented by Frank, Michalsky, and McFalls.[34] Due to the periodic need for deriveting wing surfaces on airplanes, an automatic robotically controlled deriveting system was commissioned by the U.S. Navy. The system that was developed was based on a robot mounted on a battery powered vehicle with an end-effector turret and vision system. The responsibility of the robot was to allow the vision system to scan the wing surface and when a fastener was located and identified, the proper tool to derivet the fastener was rotated into position on the end effector and the fastener was removed. The system had to be able to produce accurate location of tools, such as almost perfect normal alignment of the drill to the wing surface. Initial tests of the system were promising and full acceptance of the system seemed imminent in the near future.

General Motors has been investigating and implementing vision guided robotic systems. The need for "software fixturing," rather than hard fixturing and automation is made clear in this application. The system used in this application was implemented to tighten twelve carriage bolts underneath a partially completed automobile. A new concept was used which was the hookup of the robot to the car which hung on a monorail type conveyor. Having proved this "lockup" concept, it can now be applied to many other areas where solid connections to moving cars are needed. However, the need for vision was caused by the inaccuracy of the cars location on the carrier. The bolts were located by the vision system and downloaded to the robot controller to instruct the robot to go to the actual location and tighten the bolts. The system met all of the cycle time, justification, and repeatability and accuracy requirements.[35]

The recent demand for robots fitted with vision systems has lead to the appearance of such systems directly from robot suppliers. ASEA and Adept now provide such systems. These systems are unique in that one language is used to program both the robot and the vision system. Both systems use a teach mode in which the system is trained in both vision and robotic parameters. The applications of such systems have been in installations such as pick and place of parts from a conveyor or a pallet into a workcenter or a fixture.[36],[37]

It is quite clear that there is a vast need for the integration of vision systems with robots. A good example of this need is to solve the "bin-picking" problem. The topic of requirements and needs for vision-based robots will be discussed in later sections.

## 4.6. TEST AND CALIBRATION

The use of vision systems as part of a test and calibration system is increasing. A vision system can interpret the visual characteristics of a product in stimulus/response situations when the stimulus or response is visual in nature. Some examples of applications have been appearing in the literature.

One of the most popular applications of vision systems for test and calibration purposes has been in analog automobile speedometers, which will be described here briefly. The pointer of the speedometer is mounted loosely and the unit then placed in the test stand. Via vision feedback, a stepper motor drives the speedometer until it reads 45 MPH, and a signal is sent to stake the pointer to the pin. Next, the speedometer is driven to three different positions and an image is loaded into the system at each position. The system now verifies that the speedometer is calibrated by analyzing the pointer images. If acceptable, a final test is performed. Four more speeds are loaded by driving the speedometer and images are loaded at each level. The speedometer is then slowed to 0 MPH over two seconds, and an image is extracted every 50msecs. This test checks for speedometer bounce, i.e. uneven movement of the pointer. The odometer is checked for proper movement as a final check before the speedometer is deemed acceptable.[38]

Another application of vision system technology for testing and calibration has been for liquid crystal displays(LCDs). The product in question is activated, either mechanically or electrically, and the display calibrated and/or inspected. Examples of this have been numerous, e.g. calculators, watches, LCD displays for automobile dashboard clusters, etc. One such application has been for the test of dishwasher control panels at GE.[39] A robot actuates the panel buttons after it has been powered and a check program run. During the test, the vision system verifies that all of the displays are functional and have been illuminated in the proper sequence. At the end of the test, an accept or reject light is illuminated and a label automatically printed which is attached to the panel. This system has been very successful in terms of 100% reliability and time and cost savings. It has also reduced final assembly downtime due to checking the panels prior to assembly.

Another example of test procedures utilizing vision was seen at IBM, Lexington, KY, in the testing of typewriters and printers.[40] Printers were electronically activated and typewriters were mechanically activated to type out a set of characters on a sheet of paper. A vision system evaluated the printing to check for proper characters and legibility.

## 4.7. MACHINE MONITORING AND SAFETY

Machine monitoring via vision is the process of checking whether a machine or a tool is functioning properly. This type of diagnostics could be very beneficial for equipment that could damage itself if not shut down quickly. Although no applications could be found in the literature, it has been reported that vision systems have been used to ensure that molding machine molds are clear of parts before the mold closes for the next cycle.[1]

Machine vision for safety purposes could be used to monitor if a tool or a person enters a dangerous work area. In a sense, vision systems that operate in hazardous areas, replacing humans, could be interpreted as being in a safety application. However, as with machine monitoring, no applications have been found. In addition, no vendors advertise the use of their systems for this application. This may be due to the fact that even 99.99% reliability is not good enough in the protection of life and limb.

# 5. CURRENT CONSTRAINTS OF MACHINE VISION

As with any new technology, there is always a need for technological improvement from the current state of the art. Machine vision technology is no exception. There have been several needs for future improvements of machine vision technology identified. However, again as with any new technology, there are constraints in the application of new technology. The application problems can be considered problems in the management of new technologies.

This section will be separated into two sections, the first dealing with the technological constraints and the second dealing with problems in the application of new technology. Research that is being done to solve these constraints is examined in Section 6 of this thesis.

## 5.1. CONSTRAINTS OF CURRENT TECHNOLOGY

Vision system technology has had many advances in the last five years. It is projected that the need for improvements will continue over the next five years at a faster rate. The purpose of this section is to identify the areas where constraints in the current state of the art are hindering the possibilities of application.

It is felt that some of this problem may be caused by vendors overstating the capabilities of their system to the unwary user. When success does not occur, it automatically points to deficiencies in the technology. Users must try to understand the current state of the art of the technology before trying to apply machine vision systems.

### 5.1.1. 2-DIMENSIONAL

Most application of machine vision to date have been two dimensional systems. The limitations presented by a two dimensional strategy are obvious. The parts that are viewed must be located in a plane that remains equidistant from the camera. The only factor that relates the scene to the camera is the magnification or scale factor of the system, which is determined empirically.

There has been some initial work in trying to resolve the three dimensional problem. Some of the techniques used so far, with success, are now described briefly.

Structured light has been used to determine the object's height in the direction of the camera. A famous example of this approach is the CONSIGHT system of General Motors. This approach consists of using an angled beam of light that appears to move from side to side in the image as the object that the light is striking is moved in and out of the camera axis. This system resolves the distance problem, but only the area of the object that is illuminated can be measured.[41]

Two camera systems, or stereo systems have been used to resolve the distance ambiguity. Both cameras are angled with the object and view it simultaneously. Both cameras look at an "interest point" on the object and calculate the distance to the object, since it can only be in one location in space to produce a certain image in both cameras. In addition to the expense of a two camera system, the major drawback is the need for easily identifiable points on the object in the regions of interest.

Another new approach to the three dimensional problem is the use of structured light with a two dimensional system. These can be done simultaneously by thresholding techniques or in sequence. The process allows the whole object to be viewed, rather than just the area illuminated by the structured light.

The technique of two dimension with autofocus has shown some promise. Special circuitry is used to move the fixed focus lens in and out of the plane of the object. The third dimension is usually read out while the two dimensional processing takes place normally.

However, the application of these techniques has been limited, as is the scope of their potential use. Active three dimensional systems will be needed to truly be useful in machine vision applications. Systems for three dimensional vision are being researched intensively. Research technologies such as shape from shading, integrated range sensors, and model based systems are discussed in Section 6 of this thesis.

### 5.1.2. COLOR

The use of color analysis of industrial scenes has not been exploited by the machine vision industry. Perhaps the reasons for this are the expense of a color camera and the required processing time. However, the need for color perception and analysis is very real.

In the past, many parts were color-coded for ease of assembly by humans. Examples of this are numerous, such as color-coded wires and resistors. It seems that if vision systems could perceive and process color, many scenes that are currently difficult to quantify could be enhanced by color-coded parts.

The difficulty of scene analysis in gray scale lies in the separation of the objects from the background. This situation can be simplified if the attribute of color is used in the image and subsequent analysis.

There is a need for the development of an inexpensive and fast color detection system that can be used in machine vision systems. This type of system will add more tools to be used in the successful application of machine vision systems.

### 5.1.3. SPEED

Speed of processing of imaged data is one of the most commonly heard constraints of machine vision systems. Due to the sheer amount of data that must be processed, real time response has been limited to systems that are fairly simple in nature, or systems that have slow enough manufacturing cycles to allow full processing of image data on every part that is manufactured.

Today's push in zero-defect quality has led to a mindset that parts must be inspected on a 100% basis. Seemingly, if statistical process control techniques were implemented on a sampling basis to vision data, rather than on a 100% basis, speed of processing would not be as critical. As with computer technology, which is central to machine vision systems, the speed of processing due to hardware improvements alone will increase in the future. Until that increase is achieved, which incidentally will be required as pixel resolution increases, sampling techniques may be implemented to use machine vision systems at today's speeds.

For example, the cost and processing time to complete a fixed amount of data processing has decreased dramatically since 1975. The cost has been reduced from $0.20 to $0.07 and the processing time has been cut from four seconds to one second. Further improvements of this magnitude in the future will greatly benefit vision systems.[42]

Other techniques have been implemented to help reduce the impact of speed as a constraint. Some of these techniques are; reduction of image size by windowing, multi-processor use, reference image comparison, thresholding, and other preprocessing techniques. Speeds are also increasing due to the implementation of algorithms into hardware.

Wright and Englert suggest a breakeven type graph between processing speed and performance of vision systems. As the application requirements move towards edge detection and three dimensional processing of data, the current state of the art requires slower processing speed. The future improvement in processing speed will serve to move the downward sloping curve to the right, achieving a better performance index.[43]

There is a considerable amount to research being done in processing speed improvement via hardware improvements. An example of this research is in parallel processing and specially designed hardware such as the National Bureau of Standards(NBS) PIPE system. These research areas will be presented in the technology research section of the paper.

### 5.1.4. LANGUAGE/ALGORITHM

The development of algorithms and languages for machine vision use has been instrumental in the growth of the vision market. One of the most popular algorithms that revolutionized processing was the SRI family of algorithms. These algorithms were modified by many different vendors to suit particular needs and are still widely used.

Early vision systems were programmed in languages such as BASIC, PASCAL, and FORTH. These languages were not easily understood and used by vision applications people. This lead to a variety of programming methods and languages. Current programming methods use menu driven approaches or dedicated higher level languages.

As mentioned earlier, many companies are implementing software into custom designed, task-oriented chips. Alternately, other companies are spending more effort in areas such as algorithm improvement and fine tuning to achieve increased processing speed, while waiting for standard hardware speed improvements.

A complete review of languages and algorithms for machine vision is beyond the scope of this paper. It will suffice here to say that through the evolution of machine vision systems, a number of approaches to languages and software have been infiltrating the market. This has caused a constraint in terms of standardization and interfacing of vision systems, either by themselves or in conjunction to other factory equipment and controllers. This problem will be addressed in later sections.

### 5.1.5. RESOLUTION

The current state of the art in sensors, namely cameras, allows for only a certain degree of resolution. In terms of area or matrix array cameras, present day practical limits appear to be around 500x500 pixels. In terms of line scan cameras,the present day limit is about 2048 pixels. The need for greater resolution is needed, especially in areas such as close tolerance measurement.

However, as resolution increases, processing speed decreases. This underlines the need for both of these areas to be improved simultaneously.

Many times, there are accommodations that can be made in an application to improve resolution without the need for better resolution cameras. Examples of this are multiple camera segmentation of the image, fixed part reference locations, step-and-repeat part coverage, and subpixelation techniques. The need for better resolution is directly related to the need for improved accuracy and precision.

The trend for better resolution seems to be in solid state based cameras rather than in tube based cameras. The expansion of array sizes in tube based camera seems to be limited by uncertainties that exist in beam-addressed devices, such as scan velocity changes and peripheral non-orthogonal landing of the image beam.[44]

### 5.1.6. ENVIRONMENT/LIGHTING/SURFACE INTERPRETATION

The constraints of the environment of a machine vision system are being reduced, but still do exist. In initial vision systems, the part in question had to be perfectly fixtured. But recent software techniques have been perfected to allow for the automatic alignment of the part in the scene. These alignment techniques are limited to the amount of misorientation that is allowed.

There is a need to move away from custom jigs and fixtures, and allow the use of universal jigs and fixtures. As an example, for true flexible manufacturing systems to exist, a generic fixture has to be used to roughly fixture a part, and the vision system should take over and provide the accurate alignment.

Although some self alignment techniques do exist, the environment still has to be somewhat structured in most current applications. Current research has started to address this need in part recognition and orientation schemes such as in the popular bin picking problem. Again, one can see the tradeoff between increased software alignment versus processing speed.

Another important constraint of vision system technology is lighting in terms of constancy and sufficient image contrast. Degradation of light intensity due to service life and other factors such as dirt and ambient light changes often caused contrast problems in early systems. With the advent of better light sources, gray level processing, and histogram thresholding, many constraints have been relieved. However, ample image contrast must be maintained to allow for accurate processing of scene information.

Typically, features that must be recognized should be distinguished from local background by at least 15 to 25% of the total image intensity range. More of this constraint can be reduced by the proper design of parts to enhance features that must be analyzed. Other improvements in areas such as color detection may also improve the image contrast of a scene for analysis.

In a related topic, vision systems must be able to accurately interpret surfaces. Typically, image contrast is not a problem in applications that are back lighted, providing a silhouette that has enough contrast. However, front lighting must be used for applications that require surface analysis, such as flaw detection and recognition. Current systems do not allow for the interpretation of parts with complex surface configurations. Typical problem areas for surface analysis are texture, shadows, and overlapping parts. Once again, the bin picking problem is an excellent example of the inability of current systems to interpret variations in light intensities over the surface of an object.

Some systems that have recently been released have made advances in surface interpretation. One such device is the Applied Intelligent Systems, Inc. PIX-SCAN system. The system is designed especially for the inspection of inside and outside diameters for surface flaws. Typical application have been in the inspection of automobile engine cylinder bores and piston ring grooves.[45]

As mentioned throughout this section, the application of vision to robots has exemplified the constraints of machine vision technology. As one can easily deduce, the constraints of machine vision are greatly interrelated. For example, as stated earlier, resolution enhancement causes a subsequent increase in processing time. When applied to robots, vision systems should process in real time or within the cycle time of the robot on a parallel basis (this does not include "eye-in-hand" applications such as a robot based measuring system). Parallel improvements will be required in machine vision processing speed as robot speed increases.

In one instance, machine vision capabilities are currently exceeding robotic capabilities. The use of a vision system mounted on a robot arm for measurement of objects is limited by robot positional accuracy and repeatability. For example, a commercially available system made by Diffracto, Limited, has a vision system accuracy of +/-0.01mm, but due to robot positioning accuracy, the overall system accuracy is only +/-0.08mm. Future improvements in robotic accuracy will enhance the use of vision guided robots.

The concept of bin picking has sparked research into vision systems and vision guided robots. The purpose of the following paragraphs will be to highlight the current constraints of machine vision as they relate to the bin picking problem.

The bin picking problem can be defined as the successful robotic acquisition of randomly oriented overlapping objects in a bin. The need to accomplish this task is considered to be important if true flexibility of manufacturing operation is to become a reality.

The first problem encountered in this task is the lighting of the parts. The lighting scheme must be able to illuminate the bin evenly in all dimensions, including depth as the bin empties. Lighting must provide the proper shadowing and reflectance properties, depending on the image processing algorithm used. Surface features and edges are critical in this application.

Because the bin picking problem is a three dimensional problem, as are most industrial problems, the system must be capable of gathering and processing image data in all dimensions. This highlights the need for active range finding devices or techniques.

The speed and resolution of the system are also important. Processing speed is critical due to the manufacturing cycle requirements. Resolution requirements are high due to the amount of information that must be gathered, especially when parts that are smaller are tried.

Algorithms seem to be the key to success in the bin picking problem. Smarter and faster algorithms will be needed to allow systems to actually solve the bin picking problem. Many different software operators are being used in algorithms to enhance the image such that features and individual objects can be identified.

The condition of overlapped parts causes the objects to be obscured and not fully visible. Surface interpretation techniques as well as model based comparisons and feature estimation are necessary for the accurate recognition of the part that is to be acquired by the robot gripper.

In summary, the bin picking problem currently exhibits the constraints as well as the state of the art in vision systems. Typical research applications of the bin picking problem includes the integration of other sensors such as tactile or photoelectric sensors with the vision system in order to provide a more optimal solution.

### 5.1.7. LACK OF INTEGRATION

The lack of integration of vision system technology with other technologies has been evident in all but a few of the applications reviewed. Typically, the problem does not seem to be a technology problem, but rather a problem in either the management of technology or in the interface of technology. This topic will be addressed in section 5.2.4.

## 5.2. CONSTRAINTS IN APPLICATION OF CURRENT TECHNOLOGY

Again, there are constraints in the application of new technology in industry. This applies to any technology, not just machine vision technology. The purpose of this section is to identify the current problems that are found in attempts to successfully apply this new technology.

This section is intentionally kept brief due to its pertinence to any new technology. The section would read the same if the words machine vision system were replaced by any other new technology or product such as robotics, computers, etc.

Perhaps the largest need in any of the newer manufacturing processes is the need to be able to integrate the processes into a manufacturing system. The final part of this section will discuss the lack of integration of most applications of machine vision systems to date.

### 5.2.1. USER KNOWLEDGE AND ACCEPTANCE OF VISION TECHNOLOGY

Since vision technology is new, user knowledge and acceptance is currently low. Many times, a few relatively simple applications are needed within a company for user knowledge and familiarity to develop. Vendors and independent consultants of machine vision systems often recommend that a company's first application be a turnkey system provided completely by a vendor. This type of system would allow the user to become more familiar with the technology without assuming total responsibility for system success. See, for example, [46].

Companies that wish to start learning and implementing vision technology, as well as other new technologies, can take a number of approaches. One of these approaches is to use outside independent consultants. These consultants can help guide a company through some initial applications. Other approaches include the development of a central organization that supports all of the company's vision needs. (In fact, some vision companies are outgrowths of this type of central organization.) And finally, a company can develop its own technological knowledge. This can be done by two approaches; a "broad front" approach or a "competence center" approach. The broad front approach consists of a corporation allowing (or directing) discrete areas to install vision systems. This causes each area to individually learn about vision and then to implement their own systems. The competence center approach consists of having a group of people, versed in vision technology, helping manufacturing areas in implementing and developing expertise in vision systems. This approach seems to be the best, allowing for technology transfer and not allowing the "reinvention of the wheel".

Another problem, acceptance by workers and engineering also surfaces whenever a new technology is brought into a company. Technologies such as robotics and vision seem to have a negative impact on employees due to the elimination of jobs. This aspect must be carefully considered by management to allow for the smooth integration of vision into the manufacturing process.

### 5.2.2. COST/JUSTIFICATION

Many vision systems used for stand alone inspection applications cited in the literature met current justification parameters that companies had in place. Most systems justification are based on the reduction of direct labor cost, and payback periods of less than a year are common. However, the cost is still sufficiently high to preclude the widespread use of vision systems. The rapid growth of technological improvements in the field will reduce the cost of vision systems in the future.

There has been much discussion recently on the obsolete justification procedures that are still being used. It is felt that standard justification procedures do not include many factors that are more difficult to quantify. The additional factors that must be considered, for example, are; improved quality to the customer, requirement of vision use for a new technology, faster line speeds allowed by vision with no extra scrap or rejections, and the elimination of hard fixturing.

Some progressive companies have already discarded the standard justification approach and have focused on future market potential and market share as a way of justifying advanced manufacturing purchases. The future may bring the need for some smaller companies to purchase new technologies solely for the sake of survival in competitive marketplaces or to meet the demands of a large customer. This type of longer term approach is needed to ensure survival in the highly competitive world market.[47]

### 5.2.3. STANDARDS

Due to the proliferation of computer based technologies, e.g. robotics, vision sytems, and unit controllers, there has been a vast need to be able to interface this equipment. Often times, equipment of different manufacturers needs to be interfaced. Due to the lack of standards in the industry, it has been difficult to interface this equipment.

The basis for standardization approach being taken at NBS seems rational, and is representative of problems being found in industry. NBS feels that the problem is not in the large companies, but rather is in the small companies that try to integrate manufacturing processes, such as vision. Large companies can afford to install a large manufacturing system all at once or pay the large expense of interfacing costs. Small companies, on the other hand, have to implement systems one piece of equipment at a time. It is often found that a piece of equipment that is bought will not interface properly with a piece of equipment bought six to twelve months ago.[48]

There is a need to standardize such that discrete purchases of computer based equipment will be able to be integrated into a system over time, without the need for considerable extra expense for interfacing. The need for standard procedures, protocols, and interfaces is critical for the success of system integration.

### 5.2.4. LACK OF INTEGRATION

There has been a lack of integration of machine vision technology with other technologies in industry. However, it should be noted that machine vision technology is a relatively new technology. The lack of integration is a constraint now, but hopefully, this constraint will be relieved in the future.

There have been some examples of low level integration in industry, such as the offering of a vision guided robot "off the shelf" by a few vendors. This indicates that there is some thinking about low level systems integration in industry. Of course the industry giants have been implementing vision systems into larger manufacturing systems, such as in IBM's Lexington facility, where an on-line vision system for final test of printers and typewriters was integrated with the host system.[40] But this seems to be the exception, rather than the rule.

There are many ways of integrating vision to a higher level if one takes the holistic, or systems view. Many examples can be found of the need to integrate vision with other sensors, unit controllers, cell controllers, CAD databases, MRP and material control systems, process planning and many other CAM database components.

The next section of the paper will deal with current research activities that are aimed at solving the constraints of machine vision technology and the application of that technology. The subject of integration of vision into the manufacturing system will be discussed in Section 7.

# 6. CURRENT RESEARCH INTO CONSTRAINTS OF MACHINE VISION

As identified in the last section, these exists a number of constraints in the current state of the art of machine vision technology. Therefore, the purpose of this section is to review the current research aimed at relieving those constraints. The current research is driven by applications that will be needed in the future. Therefore, the second part of this section will address the applications that will become possible or greatly improved by the removal of the current constraints.

## 6.1. TECHNOLOGY RESEARCH

There is a vast amount of research taking place in the field of machine vision. This research is being done at university, vendor, and user facilities. To try to review all of this research would be impossible. Therefore, each constraint will be briefly reviewed in terms of a sample of the research being done to alleviate that constraint. The constraints that will be addressed are as follows; 2D, lack of color capabilities, processing speed, software limitations, and the need for a highly structured environment.

### 6.1.1. 3-DIMENSIONAL

The constraint of two dimensionality is being addressed by research into active three dimensional vision systems. The research falls into three areas of classification by the technology that is used to gather depth information, namely; integrated range sensor based, model-based, and shape from shading based. An example of each is presented in the following paragraphs.

Integrated range sensors utilize a depth or distance evaluation technique to combine 3D data with planar information. An example of research into the use of an integrated range sensor with a 2D vision system is presented by Orrock, Garfunkel, and Owen.[49] The vision system combined an off the shelf camera with a solid state ranging device. The ranging device, called the Through-the-Camera Lens device(TCL), is a sensor that was developed for auto focusing of single lens reflex cameras. The device produces two signatures which are compared to each other. The algorithm compares the magnitude of signature shift with "look-up" table data to estimate range.

The sensor and camera were mounted on a robot arm and tested for identification and location performance on cylinders and washers. Test results were within specification limits. This integration of a ranging sensor and a vision system may prove to be reliable and inexpensive for use in unstructured robotic identification and acquisition tasks.

Other range sensors that are being researched are time of flight systems that utilize radar or lasers for determining distance and depth information by measuring the length of time required for the signal to strike the object and return.

Much research is being conducted into <u>model-based</u> <u>systems</u> for interpretation of 3D data. An example of this research is the work currently being performed at SRI International. This research is aimed at the recognition and location of 3D parts using a geometric model CAD data base. A brief description of SRI's approach follows.

The goal of the research is to develop a general purpose technique for recognizing and locating parts that are only partially visible in any orientation. The approach consists of using 3D part models that will help in the interpretation of range and intensity information.

The initial range mapped image is gathered by a structured light stripe range sensor that is repeated over the object(s) in question. The image is formed by the triangulation of distances on the object. Next the system determines the edges of the object(s) in the image by classifying discontinuities in the light stripes and matching them on a stripe by stripe basis. This process yields the objects' real edges without shadow edges. At this point, the system attempts to detect object specific features from the extended 3D geometric model. The extended geometric model includes additional feature lists and classification that are redundant but allow for efficient recognition. Once the features are recognized, the object is recognized and located in space. Research is continuing in areas such as the use of PADL-2 CAD data base for more complete implementation of the representation scheme and the use of different methods of detecting features and growing feature clusters.[50]

The final area of research to be reviewed in 3D machine vision is in the area of the shape from shading technique for depth perception and object recognition. The following discussion is based on McPherson.[51]

The hypothesis presented is based on the idea that the shading of surfaces in image synthesis can be modeled by one or more functions of the surface geometry (such as in CAD representations utilizing Lambertian, Phong or other models), then the surface geometry could be derived from the shading information. Most of the models presented utilize some form of surface normal vector interpretation while viewing geometries and lighting conditions are known.

However, a limitation encountered in this research is the inability of the proposed system to achieve absolute depth perception without other range measurement devices. This is because objects of the same shape but of different sizes at certain distances relative to their size will produce identical images of sets of normal vectors. Additionally, depending on the reflective properties of the object's surface, different models of shading would have to be used to optimize the accuracy of the surface analysis and interpretation.

Most of the research into active 3D machine vision is in its infancy. However, the research is continuing and shows future promise of being readily available and useful on the factory floor.

## 6.1.2. COLOR DETECTION

The use of color based machine vision systems in the future will provide more flexibility in the interpretation of images that contain more than one color. An example of the research being done into the use of color detection in machine vision is presented by Keil.[52] The approach used in this research is the use of standard color TV cameras that have a RS170 composite video output. The system utilizes a chromakeyer and a hue selector for preprocessing the color image. The chromakeyer converts the hue content of the color image into a black and white (gray-scale) TV signal. The hue selector instructs the chromakeyer to enhance the selected hue and suppress the complementary color. All other colors in the image are assigned various levels of gray depending on their positions in the color coordinate system.

Although a color image is analyzed, the resulting enhanced black and white output can be used with standard black and white machine vision systems. Although only one color can be enhanced at a time, many different images can be taken while selecting different colors to gain information about all of the colors in a scene. However, the enhancement of one or two colors is usually enough to provide the needed information. The system has been successfully used to identify color-coded wires and colored printed circuit board components.

One of the largest problems confronted by research into color systems is the amount of information that must be processed. Using the standard red-green-blue analysis, at least three times as much information must be processed, reducing the speed of analysis. Additionally, the cost of equipment to do this type of analysis is quite high. Further research into color systems, cost reduction in equipment, and processing speed increases will help make machine vision with color a viable technology.

### 6.1.3. PROCESSING SPEED IMPROVEMENT

This section will review a sample of the research being done in the area of processing speed improvement via hardware implementations. Obviously, the semiconductor industry is working on processing speed improvement on a continual basis. Examples of this research is in areas such as ballistic effect transistors being developed at Bell Labs. However, this section will deal only with hardware that is being designed and built for vision applications specifically. The importance of processing speed improvement lies in the ability to interpret more complex scenes and complete higher level tasks.

There has been a great deal of work done in the field of parallel processing. Many semiconductor companies offer byte wide processors that are being used for vision applications either by themselves or in a multiple set-up. However, dedicated vision processors are being pursued. An example of VLSI technology research in parallel processing is being done at Stanford University.[53]

The research is aimed at developing a general purpose vision processor. The processor has a processing element for every picture element in the image. The individual processing elements each contain an adder, two data registers, and a result register. This hardware would allow edge operators and cross correlation between images. A prototype has been built and it has been estimated that this processor would be 2500 times faster than a mainframe computer. However, to implement this type of hardware for a full image of 512x512 pixels would require today's state of the art in VLSI technology to be improved tenfold. Therefore, this scale of parallel processing will be delayed until VLSI fabrication technology can accomplish this.

Another example of research into high speed processing of vision data is the experimental Pipeline Image Processing Engine(PIPE) system at the National Bureau of Standards(NBS).[54] The design goals of PIPE were:

- Image processing at TV field rates
- Interaction of related images
- Application of different algorithms to separate windows in the image
- Ability to use knowledge-based commands and reference images

This preprocessing system is based on multiple modular processing stages. There are three data paths through the system. The forward path is used for standard pipelined processing. Knowledge-based operations are provided by the backward path. The recursive path allows relaxation operations within individual processing stages. Also, any processing stage may pass data to any other stage via four common video buses.

The PIPE system is designed for use with a host computer. The host computer is used for programming and operating control. It is estimated that this system can process 800 million multiply/accumulate operations per second. The PIPE system is being built and marketed by Digital/Analog

Design, Inc. and is expected to be commercially available in the near future.[55]

The continued research in processing speed improvement via hardware implementations will allow near real-time or real-time processing of video images in the future. Speed improvements will also allow more complex scenes to be analyzed at rates that will allow on-line inspection and visual servoing of robots.

### 6.1.4. SOFTWARE IMPROVEMENTS

Software, or algorithm research is one of the main thrusts of vision research today. Researchers are finding that streamlined algorithms can increase processing speed. High level vision or goal oriented vision is the area of concentration for software improvement.

As mentioned in an earlier section, the model-based approach taken by Stanford Research Institute serves as a good example of the software development that is taking place and that will be needed for high level vision applications such as robot navigation.

The research being done in artificial intelligence will impact vision technology. Artificial intelligence is now addressing problems in high-level vision. These problems are concerned with the representation and relationships of model-based objects, the transformation of data between low-level information and high-level representation, and the interpretation of three dimensional images.[56]

Another area of software research in vision systems and their application is in the area of integration and control. This research being done at the Automated Manufacturing Research Facility at the National Bureau of Standards is concerned with the hierarchical control of a manufacturing system which includes vision technology. Hierarchical control will be reviewed in Section 6.1.6.

### 6.1.5. RELAXATION OF STRUCTURED ENVIRONMENT

Research into techniques providing for the relaxation of the structured constraint is of utmost importance for the success of high-level vision applications that will provide truly flexible automation. The research into the bin picking problem is a good example of the work being done to relieve the constraint of a structured environment. Again, the research being done at Stanford with model-based vision is addressing the problems connected with the bin picking task. The model-based approach tries to deal with missing image information caused by shadows and overlapped parts. The University of Rhode Island is also conducting research into the bin picking problem.

The need for constant lighting is being decreased by research into software lighting correction techniques. An example of this research is presented by Miller.[57] The approach utilizes non-linear filtering and logarithmic gray scale transformation algorithms to produce image processing techniques that are said to be illumination invariant. A few narrow applications of this technique were successful, and further improvement will prove useful.

Another research area is in the use of vision-based programmable vibratory feeder bowls. These were reviewed in Section 4.2. as applications of vision in use for sorting. Further research into these systems will allow the incoming material to be bulk fed into a programmable feeder bowl, reducing the need for "hard-tooled" vibratory feeder bowls and a structured environment. Centrifugal bowl feeder manufacturers are also researching vision-based systems.

## 6.1.6. HIERARCHICAL CONTROL

The purpose of this section is to review the research that is occurring in the area of manufacturing equipment control and interfacing. The review presented here will cover the work being done at the Automated Manufacturing Research Facility(AMRF) at the National Bureau of Standards(NBS). Although this work is on total manufacturing cells or areas, vision systems are an important part of these systems. Therefore, a brief review of the research and its impact on vision system technology will be presented.

As mentioned in Section 5.2.3., one of the goals of the NBS AMRF project is to be able to provide a methodology for standardizing interfaces between equipment while allowing for flexibility by programmable automation. The challenge is to be able to standardize procedures, protocols, and interfaces for current technology while still providing for the development of new and innovative products by equipment manufacturers.

The NBS control system is based on a modular hierarchical software system. The highest level of the system is a database that holds the design of the part that is being produced by the manufacturing system. High level goals are decomposed downward through the levels. Each level decomposes the command it receives into a set of simpler commands for the next level. At the bottom level, the commands are sent to the robots, grippers, and actuators to perform the actual work. In this design, each level has a limited scope of responsibility, independent of the specific details at other levels. This approach will serve as the basis for future modular and compatible hardware and software for robotics and real time sensors.

The overall AMRF has many subsystems such as turning and milling stations, interconnected by a robotic cart system. The horizontal milling workstation consists of a machining center and a vision equipped robot. Figure 6-1 illustrates the layout of the AMRF. The vision system uses structured lighting to project bars of light onto objects which allows the robot to locate and identify three dimensional objects whose position is only approximately known. This approach allows for less rigid structuring in terms of part presentation.

The hierarchy of control is based on three areas. Task decomposition sends commands downwards through the control system and provides inputs into sublevels of the world model. The world model is a system that inputs to the

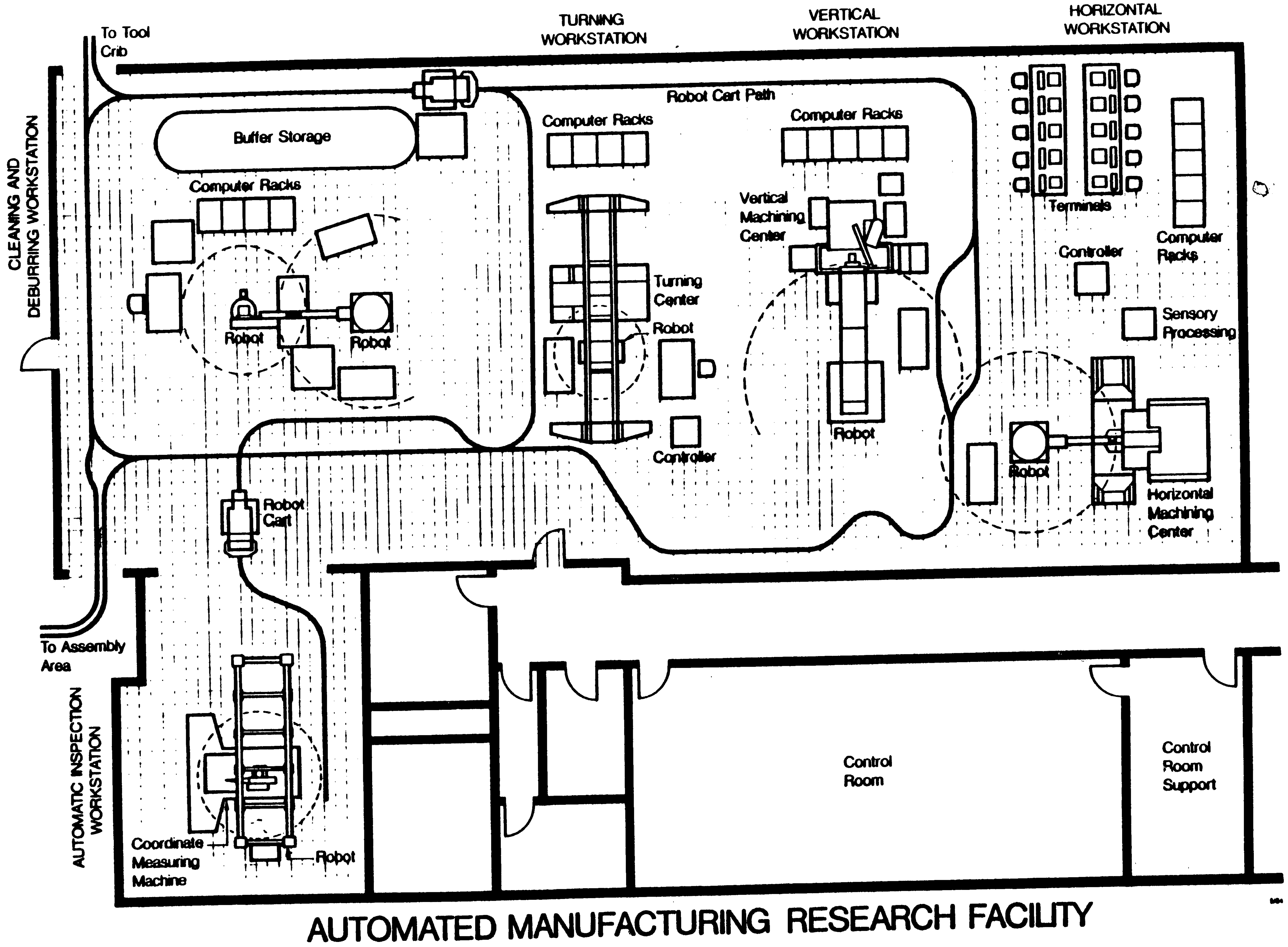

Figure 6-1: AMRF Layout

sensors what should be sensed as the "state of the world." This provides expectations to the sensory equipment, which processes feedback up the control hierarchy and to the individual task decomposition modules at each level, and also updates the world model at each level. Figure 6-2 shows the hierarchical decomposition in the chain of command for a robot in a machining workstation.

The vision system described above will serve as a good example of this hierarchical control strategy. The vision system is activated by the control hierarchy at the appropriate point in the task execution. The vision software is then told what to expect in terms of how far the object is away from the camera. This information is then used to adjust the flash intensity and gray scale threshold values along with proper algorithm selection for processing the scene. The feedback is then issued from the vision system back up the control hierarchy to inform the control system where to move the robot to approach the object or to report that the expectation was incorrect.

This research is very important in terms of providing a flexible manufacturing system. It not only allows for the standardization of interfaces, but its data driven control structure allows the use of high level part design

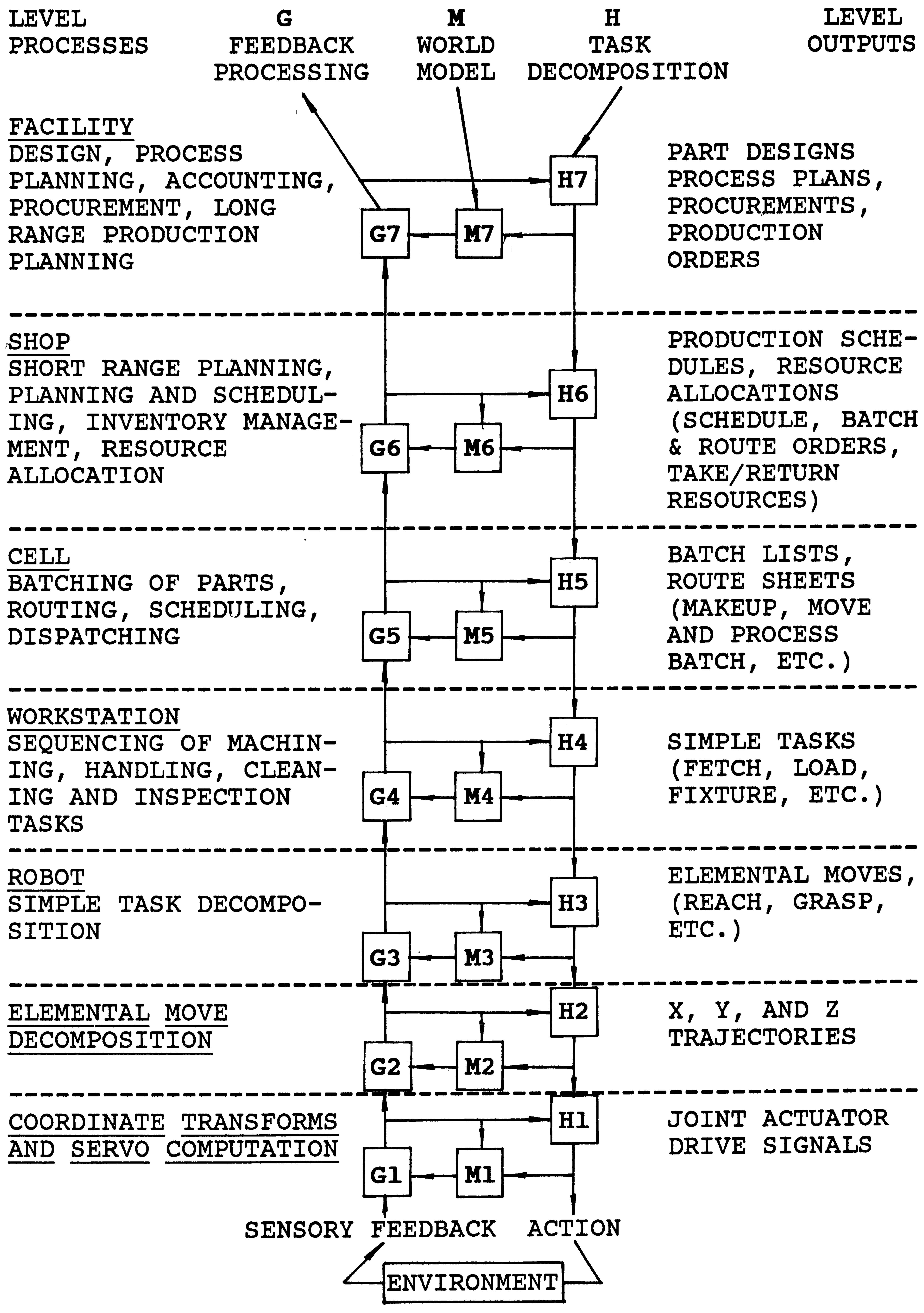

Figure 6-2: Hierarchical Decomposition of a Robot

programming that precludes any other changes when a different part is to be produced. See [48] and [58] for more information on the AMRF and the concept of hierarchical control.

## 6.2. IMPROVED AND NEW APPLICATIONS

The previous section on technology research dealt with the work that is being done to alleviate the current constraints of machine vision. In addition, some of the research is aimed at the goal of providing standard interfaces and control strategies. This research will allow many improvements in today's application technology. New applications that are not yet possible will be made feasible in the future by current research into a broad spectrum of technology including vision, computing hardware, and artificial intelligence software. Therefore, this section will provide an insight into applications that will be improved or created by research that is occurring today.

The terms low-level and high-level vision have been used to describe the general application categories of vision technology. It is useful to use these classifications in describing the future of machine vision system technology.

### 6.2.1. LOW-LEVEL APPLICATIONS

Low-level applications have been defined as vision systems that are not knowledge-based. The operations performed by these applications is usually the extraction and measurement of different shapes or features of an object. Because of the similarity of applications in low-level vision systems, many of these functions are being implemented in hardware.[56]

Therefore, hardware improvements in semiconductors will increase speed and reduce costs in low-level vision tasks. Other applications included in low-level vision systems such as enhanced 2D representations with structured light range analysis will improve greatly with hardware improvements. It may be possible to build a range or contour map without a priori knowledge of the object. These techniques may also be used for more complex surface analysis. It may be possible to use such a technique in the future to build a database for computer-aided design by mapping an object into a 3D representation of the part.

With improved color detection, many applications will be improved and created. As discussed earlier, the use of color will enhance assembly and recognition tasks when colored components are used. The ability to sense and process color information will provide many applications in the food/agricultural industry, textile production, printed-circuit board fabrication, and in the pharmaceutical industry.

As camera and system resolution improve, more complex inspection tasks will become possible if processing speed increases proportionately to today's systems. Smarter software will provide the ability to ignore inconsequential data that is in the image to allow for more efficient processing.

Software improvements will also allow for less structuring in the environment. Adaptation to lighting levels will decrease the need for constant lighting. Improvement in robotic accuracy and precision will allow "eye-in-hand" vision systems to provide more accurate and precise measurement of large objects and for improved robotic welding applications.

In summary, low-level applications of machine vision technology will benefit greatly from the general body of research that is occurring on many fronts.

### 6.2.2. HIGH-LEVEL APPLICATIONS

Knowledge-based, or goal oriented vision systems are classified as high-level vision applications. Nagel and Odrey[56] present the following description of high-level vision;

> "High-level vision is concerned with identifying a manageable goal (i.e., isolating an information processing problem) and finding a method for meeting the goal (i.e., resolving the problem). High-level vision essentially devises computational theories and proofs dealing with the problems of a task. Such systems could combine knowledge about objects (e.g., features, shapes, relationships) with expectations about the image and involve processes to aid in interpretation of the image."

Such a knowledge based approach to problem resolution is seen in two current research areas. The model-based solution to the bin picking problem being pursued at SRI International is an example of this approach. A priori knowledge of the object via a CAD database provides the missing information due to shadows and overlapping parts. Also, the hierarchical control concept being pursued at NBS uses the world modeling process to form expectations about the context of a scene as a vision system scans the scene. These types of systems will be critical in the advancement of vision into higher level applications.

With prior knowledge of a part, the amount of scanning and processing on the part will be considerably decreased.

This will allow faster processing of vision data by not forcing the system to interpret the whole object, but rather to just recognize the part and by intelligence apply whatever algorithm is needed to complete the required task.

This high-level approach to vision will allow for future applications in robotic guidance, navigation and scene analysis, and for more complex inspection. The advance of artificial intelligence will lend support to this type of application due to possibilities of allowing for faster interpretation of 3D images and providing logical linkages between object features and data base representations.

The development of expert systems may open many possibilities for vision in the manufacturing environment. Vision sensing backed by an expert system may be the ultimate tool for factory floor self-diagnostics with adaptive correction and control. An automatic machine with a vision system can almost be self-sustaining if the proper corrections and control could be integrated within the system, or at least be able to provide an accurate description to a technician of what is wrong and how it should be corrected. Although this seems rather futuristic, the state-of-the-art in vision, self-diagnostics, and artificial intelligence may allow this type of application sooner than anticipated.

In addition, the development of other sensors such as tactile and proximity sensors along with vision sensors will allow more complete data in areas such as robotic control for assembly. The integration of these sensors will provide truly intelligent robots in the future.

To summarize, the future for high-level applications of vision seems limitless. With the development of computer hardware and software along with rational strategies to link manufacturing equipment with CAD data bases, machine vision is an important factor for the successful integration of the entire factory.

## 7. INTEGRATION OF VISION INTO MANUFACTURING SYSTEMS

As mentioned throughout this paper, there is a need to integrate machine vision into manufacturing systems. However, to provide a clearer perspective, the overall manufacturing system must be discussed. The concept of the "factory of the future" has evolved as the goal of manufacturing operations. The factory of the future, or the application of computer-integrated manufacturing(CIM), must be briefly reviewed before discussing machine vision's role in the integrated factory.

### 7.1. CIM

A brief overview of CIM is presented by discussing CIM theory, reviewing the needs that are pushing CIM implementation, and discussing the problems that are faced in integrating a factory. This review provides a groundwork for the discussions that follow on the integration of vision into the CIM concept.

#### 7.1.1. CIM THEORY

The concept of CIM is a relatively new concept, grown out of the evident need for integrating both new and traditional engineering and manufacturing operations. Many architectures have been proposed to illustrate the CIM concept. Organizations such as CAM-I, ICAM, CASA/SME, NBS, and Arthur D. Little have illustrated the technologies involved in CIM and the interaction of those technologies.

The architectures proposed are similar in that all utilize computer technology to interconnect the three major areas of any manufacturing organization. These areas or functions are engineering, planning and control, and the manufacturing processes themselves. Computer technology serves as the communication network to exchange data and information between the areas. The computer is the best tool to provide this function because of its processing speed, accuracy, and the constant reduction in data processing and storage cost.

The three areas mentioned above can be further subdivided into areas of technology or function. One such subdivision of the areas is as follows;

* Engineering design and analysis
* Technical planning
* Production
* Logistical planning

- Marketing and sales

Figure 7-1 indicates these areas in a simplified CIM model along with their interrelationships. (Data stores and external entities such as customers and government are not shown.) A brief discussion of each one of these areas follows.[59]

Engineering design and analysis includes many individual functions and technologies. The responsibilities of this sector include product design, product analysis, and design classification and coding. Many new technologies that are computer based can be and are being used to improve productivity in this area. These technologies are listed and briefly defined as follows;

- Computer-Aided Design(CAD)-the use of computers for product design synthesis and storage
- Finite Element Analysis(FEA)-computer aided analysis of product designs for stresses, thermal conduction, etc.
- Kinematic analysis-computer software used to simulate dynamic system response
- Group Technology(GT)-the use of a design classification and coding scheme to group similar parts into families

For a truly integrated manufacturing operation, there should only be one data base representation of a part such that all areas of an organization utilize the same

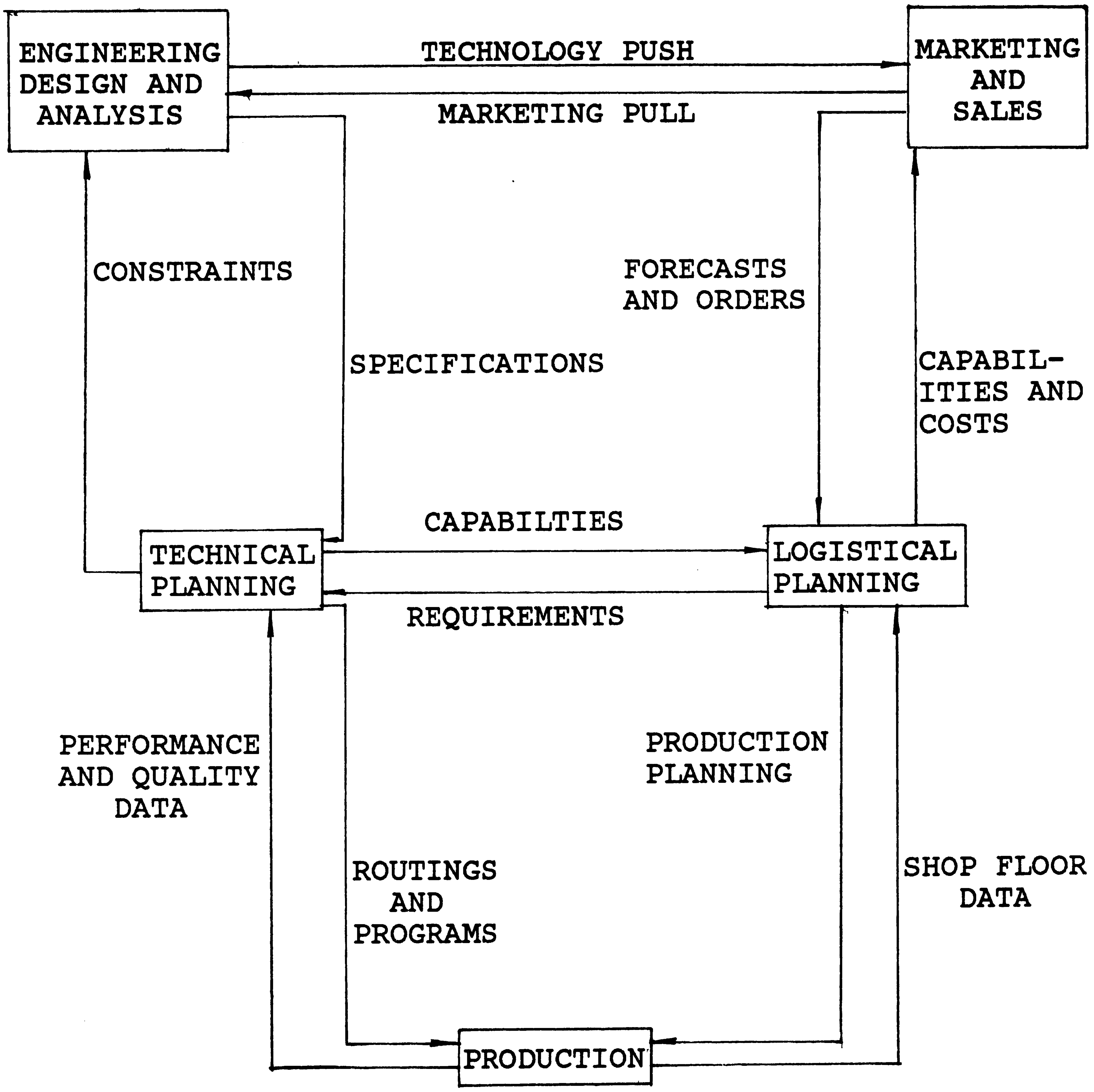

Figure 7-1: Simplified CIM Model

information. To achieve this integrated data base concept, the product design area is responsible for entering the part design (and bill of material) into the central data storage location.

The technical planning area has responsibility for process or manufacturing planning, equipment and tool design, and process classification and coding. The technologies used in this area are;

* Computer-Aided Process Planning(CAPP)-computer assisted routing generation for a product design
* Computerized simulation-the use of computer software for simulation of manufacturing facilities to aid in the design of the layout, queue sizes, required inventory levels, processing rates, etc.
* Computer-Aided Design(CAD)-the use of computers for the generation of designs for tools, fixtures, and equipment
* Group Technology(GT)-the use of a classification and coding scheme to group products into families of parts that are processed similarly
* Automatic Numerical Control instruction generation(NC) -the generation of commands for controlling a piece of equipment via a computer-based model of the product

Most of the functions described above require the use of the part design that is stored in the data base. This highlights the need for product design storage in a central data base that is available for use by other functional areas.

The production function is concerned with actually manufacturing the product. The technologies that are used on the factory floor are;

- * Robotics-the use of robots to automatically perform tasks, used alone or coupled with other equipment
- * Fabrication-NC, CNC, DNC, or otherwise controlled equipment utilized to transform raw material into a component or a finished product
- * Assembly-computer controlled equipment used to assemble components into a subassembly or into a finished product
- * Automated materials handling-equipment that automatically stores, retrieves, and transports materials throughout the factory, e.g., Automatic Guided Vehicle System(AGVS), Automatic Storage and Retrieval System(AS/RS), conveyor systems, etc.
- * Flexible Manufacturing System(FMS)-a grouping of interconnected machines and an automatic transport system controlled by a computer to carry out a sequence of operations on a product, usually without human intervention

The process instructions that are loaded into the data base by the technical planning area are used for programming the factory floor equipment.

The logistical planning area is concerned with planning, controlling, and monitoring manufacturing resources. The state of the art in Manufacturing Resources Planning(MRPII) software provides many of the tools needed to implement an effective factory management system. Some of the important modules of a MRPII system are;

- * Scheduling

* Shop floor control

* Material requirements planning

* Production planning

* Inventory planning

* Purchasing

* Capacity planning

A discussion of these topics is beyond the scope of this paper. However, it is clear that the integrated data base concept is important due to the fact that the material requirements planning system files must be derived from the part design residing in the data base. Also, current technology is capable of integrating inventory tracking software with automated material handling equipment to provide closed loop inventory storage and retrieval. And finally, it should be noted that scheduling software can download schedules to factory level controllers which are then decomposed into lower level tasks and commands via a hierarchical control structure.

The final sector of responsibility in this model is the area of <u>marketing and sales.</u> The responsibilities of marketing and sales include customer interface, order entry and processing, and sales forecasting. It will suffice here to say that marketing and sales must have access to the data base. Marketing and sales must input customer needs and requirements into the system while being able to extract information such as pricing and shipping schedules.

This review of a CIM model should generate an insight into the structure of an automated factory. The need for an accurate data base is important due to its use in all areas. In addition, the need for effective networking between areas is critical. Factory floor networks such as the Manufacturing Automation Protocol(MAP) implementation of the International Standards Organization-Open System Interconnect seven layer model are needed to be able to effectively transfer information between functional areas, while allowing for interfacing between dissimilar computer controlled equipment.

### 7.1.2. THE NEED FOR INTEGRATION

The purpose of this section is to review the need for integration. After a discussion on the need for integration, the benefits that can be derived from integrating a facility will be presented.

The need for CIM can be summed up by stating that CIM provides the productivity improvements that companies need to remain in business and be competitive. In the past, the need for cost reduction in manufacturing was fulfilled by automating processes and thereby reducing direct labor cost. However, this is no longer possible or profitable. Today's manufacturing cost consists mostly of material and overhead cost. Therefore, since a CIM strategy can effectively reduce overhead cost, the current possibilities for cost reduction are addressed.

World competition has been forcing many different pressures on manufacturers. These pressures are causing problems in the following areas;

* Greater price and quality competition
* Variation in product design
* Shorter product life cycles
* Shorter product lead times
* Rapid technological change
* Shortage of engineering talent

All of these factors are forcing manufacturers to concentrate on overall productivity improvement. All of these factors are addressed by CIM and the manufacturing technologies it encompasses.

New manufacturing technologies are becoming more complex in terms of control. The result of this is the trend toward computer control. In addition, the plethora of information that is required by and generated from all of the components of the overall manufacturing operation readily shows the need for integration.

A successful CIM installation provides many benefits that relieve some of the aforementioned problems. A CIM installation provides the information and interaction needed between the areas of an organization to provide long term benefits, rather than short term benefits that have been concentrated on in the past. Some examples of these long term benefits are increased flexibility, reduced new product transition cost, and the emergence of common goals across the organization. These benefits will be briefly discussed in the following paragraphs.

There are many advantages of flexibility if it is built into software rather than in the equipment. Changes in product mix and product changes can be handled much more easily and quickly. In addition, with a flexible manufacturing environment, work in process and finished goods inventories can be reduced due to the swifter response time.

New products can be introduced with less cost and time in a CIM environment due to its inherent superior flexibility over hard automation. The areas of CAD, CAM, and CAE also improve the response time to new market requirements.

And finally, due to the integrated data base, all aspects of the organization utilize the same information, thereby reducing or eliminating the common confusion over data and information. The interdependence of this type of system forces decisions and goals to be synthesized with the overall corporation in mind, rather than for the benefit of an individual area.

Many other benefits of CIM exist in areas such as improved product quality, tighter material control, and improved management and decision making. However, some problems exist in the implementation of the CIM concept. These will be reviewed next.

### 7.1.3. PROBLEMS OF INTEGRATION

As with any new technology or manufacturing concept, some problems exist. These problems will be briefly reviewed to provide a balanced representation of the CIM concept.

Nagel[60] cites problems in CIM implementation in three main areas; nationally, organizationally, and as individuals. National problems include the inability of CIM suppliers to provide entire systems due to their narrow focus, the competition between older solutions that are currently used and CIM, and public fear over new technology. Problems faced as an organization are; the scarcity of resources such as time and money, the disruption of operations, the required organizational changes, and the time horizon and evaluation criteria for capital spending is not long term which is required for the evaluation of CIM. As individuals, the problems involved in CIM implementation are the lack of knowledge in the technology, changing support skills that are needed, changing management philosophy, and the lack of training, retraining, and continuing education of employees.

This brief review of CIM will serve as a foundation for the following analysis of the role of machine vision in the factory of the future.

## 7.2. THE ROLE OF MACHINE VISION IN INTEGRATED MANUFACTURING SYSTEMS

The concept of CIM depends on the transmission of data between the various sectors of the manufacturing organization. In part, this data is generated by computer-based manufacturing equipment during the execution of high level commands. However, additional information must be generated by sensors to provide the control system with accurate data on the process that is being executed. This signifies the need for a sensing technology such as machine vision to provide information about the process.

This section will be dedicated to the role of machine vision in the CIM environment. Initially, the need for vision will be reviewed in terms of the type of information that must be gathered by vision systems. The following sections will discuss the integration of vision into process level manufacturing and into the CIM strategy.

### 7.2.1. THE NEED FOR VISION

There is a vast amount of process related information needed for CIM. This information can be classified into three categories which are; production control, inspection, and process monitoring. Each one of these areas is defined and examples of applications presented.

The category of information needed for production is very broad. Material handling, process control, and robotic guidance are the typical areas of manufacturing that require information about workpieces.

Material handling aspects of a manufacturing system require that parts are identified so that they are routed to the correct inventory location or workstation. Once the parts are in a workcell they must be recognized and their orientation known before processing can begin. If the workcell is robotically controlled, information about the part and workcell obstacles and fixtures must be provided to the robot controller for successful completion of the task. Non-robotic workcells such as automated assembly or machining equipment also require information about the workpiece. Information such as part identity and orientation is needed for processing to begin.

Examples of applications of vision for production control are many. In material handling, many low-level vision systems are being used to facilitate part handling. Typical systems use alphanumeric or bar code identification techniques to gather information about the part. These codes may be directly on the part or on the packaging material. Vision sensors such as bar code scanners are being used to identify the parts and pass their identity to an operator or a host computer to allow for their proper routing and to allow for part tracking through a manufacturing system.

Workcells in the manufacturing system can utilize machine vision systems to provide data on the part. Recognition and orientation information can be derived from a vision system and transmitted to the workcell controller. Applications include sorting, palletizing, conveyor picking (with or without overlap), and bin picking. Robotic workcells must also utilize vision system knowledge of the workplace for path generation and obstacle avoidance. This application of vision allows for workcell flexibility and a less structured environment.

The next category of information requirements is in the inspection area. The inspection of parts requires much information to be gathered about the part's attributes. Machine vision applications started in part inspection and techniques are becoming quite advanced. Inspection by vision applications include surface flaw detection, dimension checking, process verification, component verification in assemblies, hole location and others. This inspection information is needed throughout the manufacturing system, especially before and after workcells to check input and output part quality. The push for improved part quality has lead to applications of vision for inspection and adaptive control. Adaptive control utilizes information gathered by the vision system to provide feedback to the process controller to correct the process to a nominal level.

The final category of information required in a manufacturing system is the need for accurate data for process monitoring. The monitoring of process conditions is imperative to the successful implementation of automated equipment. In the past, automated equipment was designed to run without any consideration of what was occurring in the process. All too often, machines continued running when they were making defective parts or when they were destroying themselves. Applications of vision system technology that provide machine monitoring are many. Tool and part number verification, tool wear measurement, and process data logging are examples of the use of vision in machine monitoring. This data, along with inspection data, can be logged and statistically analyzed for trend monitoring and record keeping.

The applications mentioned here and throughout this thesis represent the attempts to satisfy the need for process information. This process information is needed to implement truly automated processes and factories that are flexible in nature. It is evident that machine vision systems can provide the information needed to achieve the goals of CIM.

### 7.2.2. INTEGRATION OF VISION AT THE PROCESS LEVEL

Throughout this paper, many aspects of machine vision have been presented and discussed. Low-level applications of vision in industry have been increasing rapidly. These applications have been mostly in the area of quality assurance. However, the future of machine vision technology and applications also includes the integration of machine vision with other processing technologies. The research presented earlier indicates the work that must be done to relieve the current constraints of the technology. But the current state of the art of machine vision allows many applications and also allows for the integration of vision with other processing technologies.

Some integration of vision technology with other technologies has begun to emerge. Examples of this integration were mentioned in the applications section of this paper in areas such as robotic guidance and process control. The availability of vision-equipped robots is increasing due to the evident need for this marriage of technology for flexibility and for coping with an unstructured environment. Process control applications such as printed circuit board component insertion equipment have evolved utilizing machine vision to provide feedback for proper insertion. However, complete process control is the future goal for printed circuit board manufacturers, which requires machine vision technology.

In the past, printed circuit board manufacturers used vision technology to inspect assembled and soldered boards. The location of defects prevented the shipment of defective boards, but manual repair costs have become a proportionately higher percentage of manufacturing cost. This stimulated the need for backward integration of vision technology in the manufacturing process to aid in the placement of components.

Carlson[30] describes the need for a total solution to automate printed circuit board manufacturing. A vision-based process monitor is now able to identify improper placement of pasted surface mount devices in a few milliseconds after placement. This system is backed up by a data base that is used to define errors and what repair actions are needed. This information, error location and repair procedure, is provided to a repair person who carries out the work. However, Carlson notes that since all the required information is available for repair, the total solution is now at hand. A repair robot could be downloaded with all of the error information to correct the error. This robot could remove the improperly placed component, remove the paste, and apply new paste to ready the board for another attempt at placement.

It is this type of system integration that will fully exploit the capabilities of machine vision. The integration of companion technologies such as robotics and vision will allow for great cost reductions and quality improvement in manufacturing processes. Other robotic sensors such as force, torque, and tactile sensors are improving and combined with vision will provide more optimal solutions to robotic tasks in the future.

### 7.2.3. IMPLEMENTATION OF VISION IN CIM

As discussed in the previous section, machine vision is beginning to be integrated with other technologies at a process level. But the future of computer-based manufacturing lies in the overall integration of the manufacturing process. The CIM concept requires that machine vision provide the necessary information to link the sectors of the manufacturing organization. These sectors, mentioned in Section 7.1.1., will be reviewed individually to indicate how machine vision technology will be integrated into the manufacturing system of the future.

The engineering design and analysis area will be responsible for entering the part geometry into the data base. Solid modeling techniques are becoming more advanced and provide the required information for further use of the data. Examples of subsequent use of 3D solid models are in areas such as NC path generation and computer-aided process planning. Vision systems will be able to use solid model data for interpreting scenes requiring a model-based approach. This has become evident in research such as that being done at Stanford on the model-based approach to the bin picking problem.

One of the goals of CIM is to provide flexibility. This flexibility can be achieved by implementing a software driven manufacturing system. This implies the use of universal tooling such as jigs, fixtures, robotic grippers, feeders, etc. If this level of flexibility is to be reached, the data base representation of the part must be accurate and unique in the sense that only one representation exists on which all sectors base their efforts upon.

The technical process planning area is responsible for implementing the manufacturing process. The use of the 3D CAD model is imperative in planning process parameters, as well as production floor control strategies. In the future, vision system parameters will be downloaded from the central or distributed data base. Examples of this include the identification of critical processing dimensions by engineering so that these dimensions are checked during the manufacturing process.

The concept of flexible manufacturing systems will require that changes are made at the control level rather than at the factory floor tooling level. Robotically controlled workcells that are vision-equipped will be provided with information about the part geometry such that identification and orientation can occur. The research at NBS in the area of hierarchical control emphasizes this point. The world model portion of the hierarchy requires that part expectations be provided to the vision sensor which will be available from the data base representation in the future.

The technical planning process will be the link between design and production, enabling an organization to meet productivity and flexibility goals. Machine vision is evolving as a key technology that will provide this link.

The production sector of the CIM environment will be where vision technology is used. Process control and monitoring parameters will be implemented by vision technology's ability to check the parameters and provide feedback for adaptive control. The application of vision will become increasingly dependent on higher level representations of the part in distributed data bases. This will potentially reduce the cost of vision systems due to the reduction of redundancy in part data base representations.

The amount of precision tooling and part orienting mechanisms will be reduced due to the ability of vision systems to provide alignment by feedback. Other uses of vision in flexible manufacturing systems will include part identification for sorting and routing, process verification, and guidance for robots and automatic vehicles.

In the CIM concept, the production process is closely linked with the logistics planning area. Production schedules and production feedback will be done automatically through company wide networks. Plant level controllers will download schedules into cell controllers that carry out the tasks and provide feedback information on actual production. Again, vision technology will provide the link between these areas to help provide companies with accurate MRPII data bases for material procurement and control.

Quality monitoring and assurance data, trend analysis, and yield information will be automatically provided by vision technology. Equipment and process maintenance will be enhanced by data acquisition performed by vision equipped workcells.

Material handling equipment now uses low-level vision systems to track and route material through a factory. The use of scanners for bar codes is being increasingly used in conveyor and tote-stacker systems. The tracking of parts and fixtures throughout the manufacturing process such as is being done at IBM's Lexington facility will serve as an important part of the production monitoring and control system.

This integration of facilities and functions will not happen quickly. Few companies can afford to utilize a "green-field" approach to build the factory of the future. Only companies such as GM, in planning its Saturn facility, can afford this kind of expenditure. The factory of the future will evolve slowly by the acquisition of knowledge by users of the new technologies. Vision system technology, along with other technologies such as robotics, CAM, etc. will advance within companies as engineers become more familiar with the technology by using it routinely. This will enable vision technology to be useful in providing true flexible automation.

# 8. DESIGN FOR VISION INSPECTION OF COMPONENTS AND ASSEMBLIES

The ability of a vision system to analyze an image easily, repeatedly, and accurately is dependent on many factors. One of the possible areas of improvement in image enhancement is in the design of the components and assemblies themselves. Simplification and feature enhancement in design can help vision systems tremendously.

However, design for inspection is only a small portion of the overall design goals. The design process has to include many areas as a whole to be able to synthesize a truly efficient design. The areas that need design consideration include design for production, distribution, consumption, and planned retirement.[61]

The area of design for production includes the topic of design for inspection. The need for efficient design for inspection highlights the need for a close working relationship between the product designer and the manufacturing systems engineer.

When a vision system is added to an existing product's manufacturing process, some changes in design can usually be made to enhance the inspection process. In addition, currently non-functional areas or attributes of the part can cause anomalies in the inspection process. These considerations will be reviewed in this section.

However, future or new designs should already include enhancements for design for inspection. The changes or enhancements made to existing designs should be implemented on the front end on new designs. This topic will also be discussed in this section.

## 8.1. MODIFICATIONS TO EXISTING DESIGNS FOR ENHANCED VISION INSPECTION

The initial problems that are usually encountered when a vision inspection system is applied to an existing product is the variation caused by attributes of the part in the scene. These may be due to the manufacturing processes used or to the variability between component suppliers. Occasionally, these problems are caused by areas of the parts that do not directly affect the part's overall quality or function.

These problems must be evaluated, with a goal to reduce the variation of lighting in the vision inspection process. Because of a vision system's dependence on light intensity analysis, changes in the amount of light gathered by the system must be minimized. An example of this encountered by the writer was in a plastic component that was used in an assembly. Metal components were added to the inside of the plastic housing, and an assembly dimension was measured inside the housing. To measure this dimension, light was passed through non-functional holes in the housing. As was quickly found, these holes varied greatly between suppliers due to loose tolerancing and the amount of molding flash. Both of these factors caused inspection inaccuracies and had to be corrected or be accommodated for.

There are many more attributes of a part that can cause light intensity variations. Some of these are as follows; burrs on machined parts, oil or grease on part surfaces, variations in surface finish between mold cavities, color or tone variations, etc. Once these problems are encountered, they must be addressed or resolved to allow for the proper inspection of critical features.

Other changes can usually be made to enhance the inspection process. LaCoe states that design changes can immediately increase the range of possible vision applications and can also decrease system cost and engineering demands. Some of his design change recommendations are briefly described in the following paragraphs.[62]

The use of contrasting components can enhance the performance of a vision system. For example, the use of alternating black and white components in a stacked assembly can reduce processing time by eliminating the need for threshold searching. Other applications of this design guideline appear in a article by Gudorf. Gudorf states that automobile motor mount assembly inspection was greatly enhanced by making a "no-cost" color change in certain components. He also references a brake hose and fitting inspection application that was improved by applying a white stripe for fitting crimp location inspection.[63]

In an effort to enhance edge detection, the use of beveled edges can greatly improve their ease of location. In top lighting applications, the beveled edge will appear dark due to light that is reflected away at an angle. LaCoe states that surface mount device inspection can be enhanced by this process.

The marking of parts can also provide key features for vision analysis. Gaging holes in a part can be used to easily locate and orient a part in space. These holes, if accurately fabricated into the part, can also serve as a calibration device for the vision system.

To allow for uniform gray scale analysis and standardization of filters, component colors should be standardized. If component colors are standardized, much less time and money will be spent in finding the appropriate light-filter-threshold level combination that will produce an acceptable image that is easy to interpret.

Another interesting example given by LaCoe was the addition of fluorescent dye to glue which made part placement onto the glued surface very clear when exposed to ultraviolet light.

Other changes, made to the assembly process itself can enhance the vision inspection of an assembly. It may be possible to change the order of the assembly process to allow intermediate vision inspection stations to measure partially complete assemblies, rather than to try to inspect a more complex complete assembly at the end of the line at high speed. If critical dimensions on an assembly are referenced to inconvenient surfaces in terms of vision inspection, it may be possible to reference to another datum without sacrificing quality and functionality.

As individual applications are studied, the list of possible design changes for enhanced vision inspection would probably grow rapidly. The concept is to ensure that product designs are not cast in stone for arbitrary reasons, but are flexible enough to benefit from minimal cost changes that will enhance the inspection by vision properties of the part and will not detract from its quality level.

## 8.2. CONSIDERATIONS FOR NEW DESIGNS FOR ENHANCED VISION INSPECTION

New designs for products should include all of the recommendations made in the previous section for enhanced vision inspection. However, new products should be designed with the complete manufacturing process in mind. The idea of system compatibility or design for producibility must be present in the initial design of every product.

In fact, the process of designing a product for use in a manufacturing system may delete the need for a vision system. An example of this may be the change from randomly oriented parts supplied in a bin, to a structured magazine or tray of parts that do not need to be reoriented. This system design would supersede the need for a bin picking robot with embedded vision. Changes such as these must be evaluated in terms of overall cost and flexibility of manufacturing operations.

However, if vision inspection becomes a real requirement in the manufacturing planning process, the product design should be inherently easy to inspect. Critical dimensions that must be measured should be minimized by combination if possible. The optical properties of the materials used should be analyzed for reflectivity, refraction, transparency, and opacity for optimal vision inspection. It may be possible to enhance resolution by providing reference surfaces that can be located easily in material handling. For example, instead of measuring the extension of a component from the body of an assembly by filling the field of view with the body and the length of the extension of the component, it may be possible to locate the camera from a fixed surface which the assembly body locates against and then simply measuring the last portion of the component extension, which would enhance resolution.

There are many factors that would enhance the inspection by vision properties of a component or an assembly. To summarize, the key factors are the reduction in part to part variation allowed by design and the maximization of feature attributes that enhance the image of the parts as seen by the vision system. There are changes that require little or no cost to implement, such as plastic color changes; and there are changes that are more costly, such as tolerance or surface finish tightening for less variation in lighting in non-critical areas. The cost versus benefit of design for inspection must be analyzed to ensure that overspecification does not occur without proper justification in overall system cost.

# 9. ANALYSIS AND SPECIFICATION OF VISION SYSTEMS

To successfully implement a machine vision system, a specification for the system must be written. The process of writing an accurate specification is beneficial in analyzing the vision need in detail, which in turn allows the system vendor to understand the requirements completely, greatly enhancing the machine vision system installation.

Although the term vendor is used, it has a broad meaning in this context. A vendor can be a vision department within a corporation, an outside vendor, or an outside systems integrator.

The following sections of the paper will address two main issues, which are as follows; assignment of primary responsibility for system success and a methodology for analyzing and specifying requirements for a machine vision system.

## 9.1. RESPONSIBILITY SPECIFICATION

Due to the relatively new nature of machine vision technology, many companies have not yet built up an expertise base in this field. This has caused a variety of methods in the manner in which systems have been implemented in industry.

There are three basic categories of industry participants at this time; based on the system type, which are;

- Generalized, basic systems
- Custom and otherwise dedicated systems
- Producers of component parts for systems

These groups serve as a means of identifying the possible supply of vision equipment.

The first group consists of companies which offer a basic system that requires a minimum of changes and application engineering to conform to customer requirements.

The second group consists of organizations that cater to the need of companies that have highly specialized applications. These applications are usually highly technical and require a large amount of customized system design.

The last grouping, component part producers, provide unconnected components which others assemble into a complete vision system. These companies can provide components to the other two categories, as well as to systems integrators or to end users who perform their own systems integration.[64]

One can easily see that the responsibility for the successful implementation of a vision system is highly dependent on the procurement method. However, it is imperative that this responsibility be delineated clearly to ensure system success.

A vision system typically consists of a vision component and a material handling device. These two components must operate together as a system for the installation to operate reliably and accurately. Typically, vision system vendors subcontract the material handling work to companies with more expertise in that field, but retain system responsibility, which is desirable. This forces the vision vendor to prove that the complete system performs according to specification.

If a vision system is embedded in a larger piece of parent equipment, such as an assembly machine, the vision supplier should become a subcontractor to the primary supplier of the equipment. This again delineates the responsibilities clearly. The primary equipment supplier assumes overall system responsibility, not only for the equipment that has been designed and built, but also for the vision system function as part of the overall system. However, the end user must still provide a specification for the vision aspect because equipment suppliers typically do not know as much about the product as does the end user.

If a systems integration house is used to supply a vision system, they become responsible for successful implementation. One advantage of systems house use is that they can build systems with equipment from different suppliers. This can enhance the fit of the equipment to the specific application.

In summary, there are many different avenues that can be taken in the implementation of vision systems. However, regardless of which channel of implementation is used, responsibility for system success must be clearly assigned.

## 9.2. REQUIREMENTS ANALYSIS AND SPECIFICATION

One of the most critical factors in the successful installation of a machine vision system is the analysis and specification of the requirements. It is critical that the user understand both the requirements of the application and the technology of vision systems. Without an accurate understanding of both of these areas, the probability of success at a reasonable cost is limited.

The purpose of the following sections is to suggest a methodology that should be followed when analyzing the need for a vision application, as well as converting that need into a comprehensive specification. References used for the sections are [65] and [66].

### 9.2.1. OVERALL MANUFACTURING REQUIREMENTS

The initial area of requirement analysis should be the overall manufacturing requirements. This analysis should cover the entire scope of the vision application. The initial phase of analysis should review the current process and how the vision system fits into the proposed process. This stage of analysis is especially important if the vision system if being retrofitted into an existing process. New installations, such as an assembly machine with an embedded vision system, must be analyzed also for overall manufacturing requirements.

The critical factors for review in this area are;

application, function, rate, and part presentation.

The proposed vision system should be analyzed in terms of what application or applications are being considered. Typically, a vision system can have more than one application. These applications, should be analyzed and listed in terms of importance. For example, a vision system on an assembly machine could serve as a process control and a quality assurance device. Measurements are made on an assembly dimension and adjustments are made to the assembly device to correct these, while parts that are outside of the acceptable range are rejected.

Once the application of the system has been categorized, the function can be analyzed. Machine vision systems can perform more than one function simultaneously, as is often required. Using the same example of an assembly machine, the object can be analyzed for size and imperfections, serving the two functions of gaging and flaw detection.

Another critical factor of the application that must be reviewed is the rate at which the vision system must operate. The rate that is specified must be the worst case rate, which is the machine rate for the most complex workpiece, not factored for efficiency and downtime. The vision system must be capable of gathering, analyzing, and providing the required output within the rate allowed by the equipment as to provide 100% inspection of the workpieces. If only a sampling of pieces is required, such as in high speed equipment, this can be factored to the desired sampling rate.

Part presentation in a vision system is a critical factor. The manner in which the part is presented to the camera must be analyzed. The part may be in continuous motion, it can be indexed into position and stopped for a period of time, or it can be hand loaded and removed. Along with the rate of part presentation, the method of presentation is important because of the speed requirements of image formation and analysis. As speeds increase, system cost increases due to the use of higher speed cameras, mechanical shutters, or strobe light systems.

The accuracy of part registration is another critical factor. As mentioned earlier in the paper, parts can be precisely located, approximately located, or randomly located. The first requiring the least processing time and the last requires the most processing time due to software registration techniques.

The number and types of parts in the view of the system must be reviewed. These factors affect the amount of image processing that is required. Touching and overlapping parts tend to cause problems in low-level vision systems. This possibility should be reviewed and an attempt to eliminate it should be considered, such as by changing the material handling technique. And finally, the worst case motion in the direction of the camera should be quantified. Motion in and out of the camera causes changes in magnification, which should be minimized.

These overall manufacturing requirements are the initial step in formulating an accurate and comprehensive specification. These factors should be analyzed carefully and incorporated into the specification.

### 9.2.2. COMPONENT AND ASSEMBLY CHARACTERISTICS AND REQUIREMENTS

Perhaps the most common reason for vision system inaccuracy or failure is the variations in the objects that are sensed and analyzed. These variations are the result of a magnitude of reasons. The variations that can occur should be carefully researched, and samples obtained to provide the vision vendor with all possible configurations and variations that can occur.

An analysis of all the components, subassemblies, and assemblies should be made. This analysis should include the number of different parts that the system will see at one time or at any time. An estimate of future needs should be performed, in the event that these factors may change in the future.

As mentioned earlier, variations occur for a number of reasons. These variations cause changes in appearance which can affect the image analysis. Some of the possible variations are as follows:

- Size variations
- Color/shade variations
- Surface finish variations (machining marks, texture, etc.)
- Corrosion level variations
- Lubricant variations (presence, amount)
- Dirt level variations
- Appearance degradation variations (change in appearance over time)
- Supply variations (parts from different mold cavities, stamping dies, suppliers, etc.)

Appearance changes can also be caused by damage to the part during the production process. These changes should be classified as acceptable or unacceptable.

At this time, good design for inspection practices will pay off in reducing the amount of variation that can occur, while providing the highest contrast levels that enhance vision system operation and accuracy.

In summary, all of the characteristics and requirements of the parts that will be viewed by the vision system should be analyzed and samples provided to the vendor. The greater the number of acceptable variations that are designed into the vision system, the less problems will be found in debugging the system and in actual production.

### 9.2.3. ENVIRONMENTAL REQUIREMENTS

The environment a vision system will operate in is critical to its design. The environment should be analyzed and incorporated into the machine vision system specification. Both the physical and atmospheric environment should be reviewed.

The physical environment includes shock and vibration, hazards, and operating ambient temperature. Depending on the application, each of these factors can influence the successful operation of a vision system. Shock and vibration magnitude should be quantified or estimated. This will affect the camera and stage mount design. Hazards in the operating area should be identified. These hazards can come from equipment in the area, such as impact from flying debris or broken tools. The temperature range that the vision system will be operating in should also be estimated.

Atmospheric conditions in the plant can also affect the operation of a vision system. However, specification of atmospheric conditions will allow these conditions to be tolerable to a system due to design changes. If humidity is high in a plant, dry air purges can be incorporated into the system to alleviate potential problems. Other atmospheric conditions such as dust, mist, fumes, and radiation must also be evaluated for proper design considerations.

In addition to physical and atmospheric considerations, the optical and electrical environment must also be quantified. Ambient light in a facility can change or be affected by equipment. The type of lighting used and the possibility of stray light sources such as a welding torch should be identified. Suspected sources of electromagnetic and/or radio frequency interference should be identified. And

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In addition to physical and atmospheric considerations, the optical and electrical environment must also be quantified. Ambient light in a facility can change or be affected by equipment. The type of lighting used and the possibility of stray light sources such as a welding torch should be identified. Suspected sources of electromagnetic and/or radio frequency interference should be identified. And finally, the electrical power regulation system should be evaluated to ensure immunity from voltage sags and spikes.

### 9.2.4. PHYSICAL SYSTEM REQUIREMENTS

The physical requirements of the system must be identified and specified. Camera, light source, and processor mounting and access must be evaluated. This analysis should entail location of other equipment, ease of access for maintenance, and the minimization of the distance between the camera and the processor.

The utilities available for the system must be comprehensively identified, as well as the type of packaging required for the system. Depending on the industry, certain NEMA standards apply and should be adhered to.

### 9.2.5. OPTICAL REQUIREMENTS

The optical requirements that a vision system has to adhere to should be analyzed. However, it should be noted here that care must be exercised if an outside vendor is being used for the design, build, and implementation of a turnkey system. A specification is intended to serve as a documentation of user needs. It is not intended to serve as a document to inform the vendor on exactly how to complete the task. In any case, the user must still analyze the optical requirements and other requirements, even though they may not be included in the actual specification. This analysis ensures that the user understands the application and can work with an outside vendor to provide a system that is designed and built to meet the actual needs.

The field of view of the camera and lens system should be large enough to cover the size of the part. In addition, if approximate or random registration is used, the field of view must be large enough to allow the part to fit in any orientation. There must also be some allowance added if parts are moving and triggering of the system does not always occur at the same location in the camera's field of view.

The depth of field must also be designed to cover the full range of requirements. This should be designed to cover all the variations due to movement in the direction of the camera and the various heights of features on a part.

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The depth of field must also be designed to cover the full range of requirements. This should be designed to cover all the variations due to movement in the direction of the camera and the various heights of features on a part.

The method of lighting should be reviewed. The function of the vision system, as well as the configuration of the part often dictate which lighting technique should be used. For example, surface flaw detection dictates front lighting and outside edge gaging typically dictates backlighting.

The distance between the part and the camera and the part and the light source must be reviewed. These distances are influenced by factors such as maintenance access, interference, relative motion between the camera and the part, heat damage from the lamp, and light intensity.

### 9.2.6. PERFORMANCE REQUIREMENTS

Performance requirements are an important part of vision system analysis and specification. Section 10 of this paper will discuss in detail a method of objectively specifying performance requirements and a method of evaluating actual performance. This section will serve as an introduction to the subject of performance requirements.

Performance requirements must be analyzed closely to ensure that the system will indeed perform the required tasks. All data that is to be extracted from the image must be evaluated. This data includes all the measurements that need to be taken, all the features that need to be verified, the features used for identification, flaws that are to be detected, etc.

The accuracy requirements of the system must be analyzed. A quantitative specification must be used to describe the allowable tolerance of deviation from actual measurements. The method of correlation of system measurements to a standard should be designed and specified. The repeatability requirements of a system should also be quantified.

In addition to process requirements, the equipment needs in terms of reliability should be reviewed and specified. The need for maximum uptime is of paramount importance in high speed manufacturing processes. Reliability of equipment should be specified in terms of quantitative factors such as mean time between failure, average repair time, and minimum uptime.

As stated earlier, more details and a suggested methodology will be presented in Section 10.

### 9.2.7. INTERFACE REQUIREMENTS

As is evident in the literature, the need for effective equipment and computer interface is critical. Unfortunately, standards for data transmission have not been fully implemented. In addition, standard programming languages and techniques have not been made for vision systems. Until standardization occurs, if ever, care must be exercised to ensure that new equipment is capable of communicating with other existing equipment.

The interface requirement analysis should begin with a description of all the equipment a vision system has to interface with. In addition, the communication protocols should be established such that all the equipment is interconnected effectively. The trigger signal that starts the vision system must be identified. The trigger can be within the vision system itself, as in a continuous process, or an external trigger from a sensor or a process controller.

The interface requirement must also include provisions for data logging and transmission. The type of data, where the data is transmitted to, and the recording media must be analyzed and specified. Typically, statistical process data is recorded and transmitted to allow production personnel to keep track of production and error rates.

Not only is equipment interface important, but so is operator interface. The required controls should be specified. Typical controls include a CRT with or without a lightpen, a control panel, and possibly a printer. The type of graphics in menus for CRT display and interface should be reviewed and specified. This may depend on the system being considered.

Programming and changeover requirements should be considered, if applicable. Some systems do not allow programming changes to be performed by the user. If changeover between products is required, this should be built into the system and be relatively easy to accomplish.

In addition, calibration techniques should be analyzed and documented. Many techniques currently exist and are dependent on the application and the equipment. Some systems use a "hard" calibration plate while others use acceptable and defective parts as a calibration technique, known as "learning by seeing." Other systems are calibrated by the user in software or by a fixed distance measurement technique built into the system. In any case, the calibration technique should be known as well as the need to recalibrate due to product changeover, lens replacement, lighting variations, etc.

## 9.2.8. SUPPORT REQUIREMENTS

As discussed in section 9.1., responsibility for every aspect of a vision system must be delineated. If a system is integrated in house, specification of and responsibility for application software, material handling, optical design, installation, training, service, etc. must be assigned. However, if a system is bought from an outside vendor, these areas must be reviewed and specified. Training of operators and maintenance workers must be reviewed as well as warranties, spare parts inventories, and speed of part replacement. Vendors must know what is expected of them at the beginning of a vision project so that no conflicts arise at a later time.

# 10. VISION SYSTEM PERFORMANCE CRITERIA AND EVALUATION

As stated earlier, the need for quantitative requirements for performance criteria and performance evaluation is important. Without these requirements, system users and system implementors are at a disadvantage because expectations and goals become unclear. It is the intent of this section of this paper to provide a framework for establishing performance criteria and a method for evaluating system performance.

## 10.1. SCOPE

It is infeasible to review numerous application possibilities in terms of performance citeria and evaluation procedures. Therefore, the quality assurance application of non-contact measurement of an assembly will be investigated. However, criteria discussed here can be modified for use with other applications of machine vision systems.

This section will be broken down into the area of performance criteria and performance testing. The subsection on performance criteria will provide guidelines in reviewing the potential application for performance requirements. The subsection on performance testing will review methods of evaluating vision system performance by using quantitative testing techniques.

## 10.2. PERFORMANCE CRITERIA

The initial step in analyzing the performance criteria for a vision system must be the analysis of the manufacturing process itself. The abilities of the manufacturing process must be quantified before a vision system can be implemented. A vision system cannot inspect quality into a part, it can only measure the part resulting from the manufacturing process.

In addition, the application of machine vision must be realistic in terms of the current state of the art of vision system technology. The current constraints of processing speed and digital spatial resolution must be evaluated to ensure the feasibility of the measurement application. However, alternatives such as sampling rather than 100% inspection must be considered to allow for currently available processing speeds. This shows the importance of user technical knowledge of the current state of the art for the successful analysis of the vision need.

### 10.2.1. MANUFACTURING TOLERANCE AND PRECISION REQUIREMENTS

The concept of manufacturing tolerance includes the areas of component and process variability. Both of these topics will be reviewed in the following paragraphs.

Component variability is a critical factor in the analysis of performance capabilities of a manufacturing process and a vision inspection system. Inevitably, components vary in both size and appearance. Both of these factors affect the assembly and the subsequent inspection of that assembly. All of the possible variations of the components in terms of appearance should be reviewed. Since vision systems depend on the measurement of light, attribute variations must be analyzed.

Variations in component size are critical to assembly dimensions. Depending on the design of the assembly, component size may directly affect the assembly dimensions. This is true where features of the components are used to locate themselves in an assembly. In this case, the assembly process is highly dependent on the components, emphasizing the need for quality assurance on the incoming components. In other assembly cases, the manufacturing process itself sizes the assembly, independent of the size of the components. An example of this would be the insertion of a pin in a hole to a specified depth without any interlocking constraints.

Therefore, the manufacturing process must be quantified in terms of the dimensional range of the finished product. This range, along with its distribution, must be known prior to evaluating the need for a vision system. The following paragraphs will further analyze the concept of manufacturing tolerance and its relation to vision system requirements.

The key attribute of manufacturing systems that must be analyzed is the variability of the process. Typically, manufacturing processes follow a normal, or Gaussian, distribution. Certain tests can be performed on the data to ensure that the distribution does approximate the normal, such as the Chi-squared goodness of fit test. A derivation of and/or an explanation of statistical concepts used in this paper can be found in many texts. See, for example, [67] and [68].

The data collected by this analysis can provide information on the variability of the process, namely the standard deviation. Typically, a measure of the variability of the process is six times the standard deviation, or +/-3 standard deviations, which encompasses 99.7% of the process results. This range of variation should then be compared to the overall allowable manufacturing tolerance range. Depending on how much of the manufacturing range is "used up" in process variation, the required vision system precision can be estimated.

For example, when an allowable tolerance range of 20mm exists, and the process only varies through a six standard deviation range of 2mm, it would be costly and useless to require a vision system to perform in a six standard deviation range of 2mm. A vision system that would be repeatable to a six standard deviation range of 5mm would be adequate, since the acceptable limits could be reduced to cover the non-repeatable range of the vision system, without allowing for Type I and II errors. (Type I and II errors are committed when a good part is rejected or when a bad part is accepted, respectively.) Obviously, this system would only be used to spot gross defects of the part in question since the process is under statistical control.

Unfortunately, many manufacturing processes do not allow the luxury of "using up" only a small portion of the manufacturing tolerance in variation due to the components or the process itself. Usually, the entire allowable range is possible due to component and assembly variation and out of tolerance parts occur often enough to justify the need for a vision inspection system. At this point, the analyst must decide how much of the manufacturing tolerance can be "used up" by the vision system's variability, or error of measurement. A common rule of thumb used in the inspection field is that the error of measurement of the inspection device, six times the standard deviation, should be less than 10% of the manufacturing tolerance range. See, for example, [15].

### 10.2.2. ACCURACY REQUIREMENTS

Accuracy in vision systems is a by-product of precision. Once precision has been established, accuracy can be calibrated into the system. This calibration is usually performed in system software while measuring a calibration gage or a part of known size. Systems are typically recalibrated over time to reduce the effects of time based sources of non-repeatability.

However, system inaccuracy adds to the range of variation in the inspection process and should be minimized by applying a limit on inaccuracy. Also, pixel size is dependent on accuracy requirements, which will be addressed in the next section.

### 10.2.3. TRANSLATION OF REQUIREMENTS INTO VISION SYSTEM PARAMETERS

As mentioned earlier, a common rule of thumb is to require a vision system to be 99.7% repeatable within 10% of the manufacturing tolerance range. This factor, however, cannot be directly used to calculate pixel size. There are many other factors that contribute to system non-repeatability, such as lighting variation, temperature, etc., as were mentioned in section 3.8. Vision system producers that state that a system is accurate and precise to within one pixel are incorrect.

In terms of digital resolution only, accuracy and precision to within one pixel is attainable in the short term. Experimentation performed on a View 1119 system confirmed this point. When a measurement was repeated on a fixtured part, without allowing for variations in lighting, the measurement was highly repetitive. In fact, identical readings were produced over hundreds of measurements. Obviously, the distribution produced was not a normal distribution. Not until sources of variation are added does the inspection process approach the normal distribution. It is this added variation due to other sources that must be minimized to allow for accurate and precise measurement. Assuming the sources of this variation are independent and random, they should be added as the root mean square of the overall system non-repeatability.[15]

There are a number of rules of thumb in use in the vision industry, the source of which seems elusive, for covering overall system variability. This is highly dependent on the type of system and its environment. One of the rules of thumb used is that pixel resolution should be two to five times greater than originally calculated to meet the requirement of 10% of the manufacturing range. An example of this estimation procedure should clarify the process.

Assume a measurement that is to be inspected on an assembly is 10+/-0.25mm. This translates to a manufacturing tolerance range of 0.5mm. The application of the 10% rule yields a value of 0.05mm. (Incidentally, the 0.05mm value becomes the test range for six standard deviations, which will be addressed later). The field of view requirement is set at 12mm, to allow for slight physical misalignment of the part. Application of the two to five rule reduces the value to 0.025 to 0.01mm, respectively. This range is the pixel sizing range, requiring a camera range of 480 to 1200 pixels in the direction of inspection. This is a broad range, and a careful analysis should be made as to what pixel resolution should be used.

The size of the pixel to be used is dependent on a variety of factors that can affect system precision. Accuracy requirements, in this case, would be set to the pixel size used. The critical factors that should be analyzed are; system precision, multiple point measurement, and subpixelation techniques. However, in no case, should a pixel size larger than the two rule, 0.025mm in the example, be chosen if precision requirements are critical due to manufacturing process variation.

System precision factors were reviewed earlier, and it will suffice here to say that the application must be analyzed to quantify the additional contribution of each factor to overall system non-repeatability. However, in some cases, precautions to minimize the effects of these factors can be taken. For example, lighting histograms can be written in software to measure current lighting conditions and compare them to the lighting condition that was present during system calibration. If this lighting has varied significantly, the system can be programmed to shut down for recalibration or correction.

Statistical techniques can be used to improve measurement precision. If processing times allow, multiple measurements of the same dimension can be performed, and the readings averaged to produce a more precise result. Statistically, the error of measurement will decrease with the square root of the number of measurements taken.[69]

Subpixelation techniques are currently being researched with only limited success in application. The theory of subpixelation is based on a sharp optical transition at the edge of part. By measuring the gray scale value at the transition point or pixel, it would be proportional to the distance within the pixel at which the transition takes place. However, in applications to date, not all of the transitions have been sharp, and blurred edges do not allow for reliable subpixelation.

If the part that is being measured has a dimension based on a feature that is relatively small, it should be noted that for reliable recognition of that feature, it should be at least two pixels squared, (four pixels), in size. This is based on the Nyquist sampling criteria, aliasing, and other image degradation factors.[9]

In summary, pixel size determination is usually at the discretion of the system designer. However, vision system users should be aware of required resolutions for achieving desired precision levels. Pixel sizes of one twentieth to one fiftieth or less of the manufacturing tolerance should be used for successful accuracy and precision, depending on application.

## 10.3. PERFORMANCE TESTING

Once a vision system has been completed, its performance must be evaluated to ensure its capabilities meet the prescribed criteria. Statistical analysis is an appropriate technique for this evaluation. A concept for measuring device testing will be presented.

The variability of the observed readings of a measurement device is actually a sum of the variation in the product that is being measured and the variation in the measurement device. The goal of vision system testing procedure should be to isolate the variation of the measurement device from the product variation.[68]

### 10.3.1. TESTING PROCEDURE AND EVALUATION OF RESULTS

A plan for performance evaluation is critical for the accurate evaluation of a vision system. Vision system implementors frequently state that most of the confusion over system performance often stems from the lack of requirements and testing procedure communication between user and vendor. See, for example, [70].

This emphasizes the need for the acceptance testing procedure to be part of the initial machine vision system specification. The testing procedure must be presented in detail to alleviate any misconceptions of requirements.

The system testing procedure should begin with a calibration of the system. This calibration should be performed on a part of known size or a calibration plate. To isolate the error of measurement from the variability of the parts, a single part (or calibration standard) should be measured repeatedly.

Based on statistical theory, the number of measurements on the same part for each dimension in question should be 20 to 25. Each measurement should be independent of the previous reading, allowing for stabilization of the vision system. Usually a test such as this is performed off-line, unless the vision system is mounted on a piece of manufacturing equipment. Care should be exercised to be able to correlate the expected results to the actual plant environment, if the testing is done in a laboratory environment. Usually, a manufacturing environment produces more non-repeatability than a laboratory environment. Consideration should be given to final testing and approval occurring on-line, rather than off-line.

Once the measurements are taken, the mean and standard deviation of the data should be calculated. The standard deviation of the data represents the error of measurement, or the non-repeatability. The mean of the data represents the accuracy, or the true value of the measurement.

As mentioned before, a good test criteria for a measuring device is one tenth of the manufacturing tolerance being compared to six times the standard deviation of the measurement device. Therefore, once the standard deviation of the measurements is calculated and multiplied by six, it should be less than the prescribed test value. If the value is less, the system is operating within the specified parameters. If not, the problem must be found and corrected before the system can be implemented.

The mean of the test data should be within the allowable accuracy range that is specified to the true value of the mean. The true value should be derived from a part or a calibration plate that is agreed upon and can be traced back to a NBS transfer standard.[71]

Once the system is found to be acceptable to specification, a decision must be made on how acceptable errors in measurement will affect the quality of the parts that are accepted or rejected by the manufacturing process. As mentioned earlier, due to errors in measurement, acceptable parts may be rejected or unacceptable parts may be accepted. Depending on quality policy, machine vision acceptance limits may be set accordingly to achieve desired results. For example, if the goal is to never allow a bad part to be accepted, the acceptance tolerance range of the system must be set tighter by a multiple of the standard deviation. This will reduce or eliminate the number of bad parts that are accepted, but will increase the number of good parts that are rejected. Assuming a normal distribution, the frequency of these errors can easily be calculated.

## 10.4. SUMMARY

The guidelines given in the preceding section are a good starting point for analysis of vision system needs. However, due to differences in applications, the guidelines cannot be used exclusively.

Individual applications must be carefully reviewed to attempt to locate possible problem areas. In an application that was studied, a tightly toleranced industrial assembly was measured at high speeds for critical dimensions. A multiple camera arrangement was used. Certain dimensions had tighter tolerance requirements due to the configuration of the assembly. The design of the part caused poor edge detection due to spectral reflectance in the backlit area and location changes in the plane of the camera. These location changes caused focusing problems due to the limited depth of field of the system, which is required at high magnification. In addition, variations in component size and shape from different suppliers caused lighting intensity changes in the image which added to the non-repeatability of the system.

These problems that were encountered during system development and debugging caused delays and system precision degradation. In addition, precision requirements and testing parameters were initially unclear and may not have been completely understood by the system supplier. This example emphasizes the need for careful examination of the part or assembly that is to be measured, and a clear and concise statement of system requirements and testing procedures.

# 11. FUTURE DIRECTIONS OF MACHINE VISION

Machine vision is evolving as one of the major technological processes that will help bring the concept of CIM into reality. The link between design, quality assurance, and production must be made for U.S. manufacturers to stay competitive in the future. This section will briefly review the forecast for the future of machine vision. In addition, the following section will outline areas that could be pursued in further study of machine vision technology.

## 11.1. FORECAST

The vision market is expanding rapidly not only in size but in applications. To date, most vision applications have been in quality assurance. However, with the new needs for vision that are being embraced by CIM technology, the application base is shifting. According to a study by Tech Tran[72], approximately 400-500 machine vision systems were in use in the U.S. at the end of 1982, with the installed base being roughly the same. However, by 1992, the annual unit sales should reach 14,000 systems, with an installed base of 40,000-50,000 units. Additionally, by 1992, robotic control applications of machine vision should account for 25-30% of the installations, up from only 5% in 1982. These figures illustrate the growth and shift of the marketplace.

The current vision vendor market is estimated to have over 100 vendors. However, the market will not support this many vendors in the next five or ten years. Market projections indicate that many of these vendors will be bought out, sold and merged, or consolidated. The recent investment by GM in five vision companies indicates GM's belief in this technology and also provides them with a faster method of acquiring technological expertise for use in their facilities.[73] Because of the importance of machine vision technology in the integration of complete manufacturing systems, other large companies such as 3M and Kodak are entering the market.

The successful application of machine vision systems, either independently or integrated with other technologies, will continue to fuel the market. And as the application base grows due to current research into higher level applications, machine vision will become a critical part of flexible automation in a CIM environment.

## 11.2. RECOMMENDATIONS FOR FURTHER STUDY

There are many areas within machine vision technology and its application that could serve as the basis for further study. This thesis highlighted a number of topics that pertain to machine vision. Almost any of the areas discussed could be concentrated on individually to contribute to the understanding and advancement of the technology.

Since the integration of machine vision with other technologies into the automated factory of the future is of utmost importance, further related study in that field should be completed. For example, a structured analysis of the information flow within a CIM environment should be done with emphasis on the requirements of vision data throughout the system. Other possible areas of research dealing with vision system technology in the CIM environment includes data base structuring needs and data integrity concerns.

The interaction of vision systems with other systems highlights the need for standardization of interfaces, protocols, and languages. Network standards such as MAP are beginning to emerge as well as control strategies such as the hierarchical structure proposed and implemented by NBS. Many topics for further detailed analysis in these areas are possible.

Additional areas of study could center around the need for the use of artificial intelligence (expert systems) in the area of machine vision. Further developments in computer hardware and software technology will impact machine vision and the effects of these developments can serve as areas for further research into machine vision.

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