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Design and application of industrial machine vision systems

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Abstract

In this paper, the role and importance of the machine vision systems in the industrial applications are described. First understanding of the vision in terms of a universal concept is explained. System design methodology is discussed and a generic machine vision model is reported. Such a machine includes systems and sub-systems, which of course depend on the type of applications and required tasks. In general, expected functions from a vision machine are the exploitation and imposition of the environmental constraint of a scene, the capturing of the images, analysis of those captured images, recognition of certain objects and features within each image, and the initiation of subsequent actions in order to accept or reject the corresponding objects. After a vision system performs all these stages, the task in hand is almost completed. Here, the sequence and proper functioning of each system and sub-systems in terms of high-quality images is explained. In operation, there is a scene with some constraint, first step for the machine is the image acquisition, pre-processing of image, segmentation, feature extraction, classification, inspection, and finally actuation, which is an interaction with the scene under study. At the end of this report, industrial image vision applications are explained in detail. Such applications include the area of automated visual inspection (AVI), process control, parts identification, and important role in the robotic guidance and control. Vision developments in manufacturing that can result in improvements in the reliability, in the product quality, and enabling technology for a new production process are presented. The key points in design and applications of a machine vision system are also presented. Such considerations can be generally classified into the six different categories such as the scene constraints, image acquisition, image pre-processing, image processing, machine vision justification, and finally the systematic considerations. Each aspect of such processes is described here and the proper condition for an optimal design is reported.

Keywords: Design; Application; Industrial; Vision system; Image

1. Introduction

The introduction of the automation has revolutionized the manufacturing in which complex operations have been broken down into simple step-by-step instruction that can be repeated by a machine. In such a mechanism, the need for the systematic assembly and inspection have been realized in different manufacturing processes. These tasks have been usually done by the human workers, but these types of deficiencies have made a machine vision system more attractive. Our expectation from a visual system is to perform the following operations: the image acquisition and analysis, the recognition of certain features or objects within that image, and the exploitation and imposition of environmental constraints [1].

Scene constraint is the first consideration for the machine vision system. The situation of the scene must be recognized by the machine vision designer and according to the required application such a machine should be developed. The hardware for this sub-system consists of the light source for the active imaging, and required optical systems. Different lighting techniques such as the structured lighting can be used for such purpose. The process of vision system starts with the image acquiring in which representation of the image data, image sensing and digitization is accomplished. Image sensing is the next step in order to obtain a proper image from the illuminated scene. Digitization is the next process in which image capturing and image display are accomplished. The last

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step in this process is the image processing in which a more suitable image is prepared.

The first aim of this article is to describe a simple machine vision system that can be employed in the industrial applications. Second goal is to describe typical examples of the visions systems in the automated manufacturing systems. Finally, we try to present some ideas about the development of the new machine vision systems by suggesting new acquisition systems. In this respect, by the advent of the suitable laser light sources, design of a 3-D camera vision system based on the laser scanning method has been an interesting issue. Considerable efforts have been made to collect the real-time, high-resolution imagery data to provide high-quality 3-D information about the object under study. Vision systems can be considered as an intelligent sensor system for complex measuring or inspection tasks.

2. Machine vision design

The main components of a typical vision system have been described in Refs. [1–4]. Several tasks such as the image acquisition, processing, segmentation, and pattern recognition are conceivable. The role of image-acquisition sub-system in a vision system is to transform the optical image data into an array of numerical data, which may be manipulated by a computer. Fig. 1 shows a simple block diagram for such a machine vision system. It includes systems and sub-systems for different processes. The big rectangles show the sub-systems while the parts for gathering information are presented as small rectangles in Fig. 1. As can be seen in Fig. 1, the light from a source illuminates the scene (it can be an industrial environment), and an optical image is generated by image sensors. Image arrays, digital camera, or other means are used to convert optical image into an electrical signal that can be converted to an ultimate digital image. Typically, cameras incorporating either the line scan or area scan elements are used, which offer significant advantages. The camera system may use either charge coupled device (CCD) sensor or vidicon for the light detection. The preprocessing, segmentation, feature extraction and other tasks can be performed utilizing this digitized image. Classification and interpretation of image can be done at this stage and considering the scene description, the actuation operation can be performed in order to interact with the scene. The actuation sub-system, therefore provides an interaction loop with the original scene in order to adjust or modify any given condition for a better image taking.

3. Operation of a machine vision system

A visual system can perform the following functions: the image acquisition and analysis, the recognition of an object or objects within an object groups. As can be seen in Fig. 1, the light from a source illuminates the scene and an optical image is generated by image sensors. Image acquisition is a process whereby a photodetector is used to generate and optical image that can be converted into a digital image. This process involves the image sensing, representation of image data, and digitization. Image processing is a process to modify and prepare the pixel values of a digital image to produce a more suitable form for subsequent operations. The main operations performed in the image processing are outlined in Table 1. Segmentation seeks to partition an image into meaningful regions that corresponds to part or whole objects within the scene. Feature extraction in general seeks to identify the inherent characteristics, or features, of objects found within an object. Pattern classification refers to the process in which an unknown object within an image is identified as being part of one

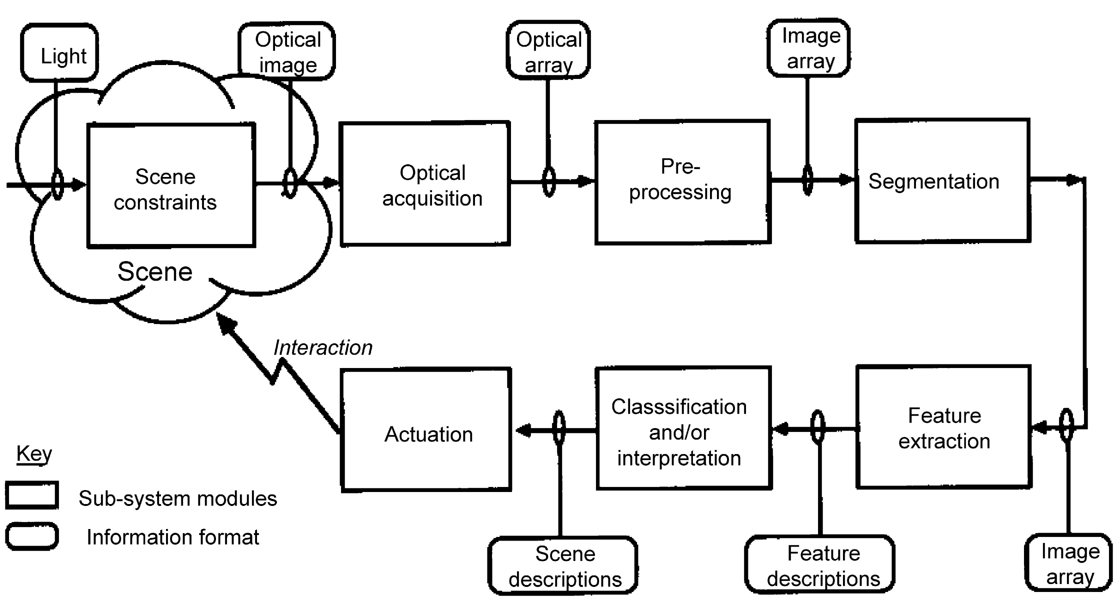

Fig. 1. A simple block diagram for a typical vision system operation [1].

Table 1
General operations performed in the image processing

Point operation	Global operation	Neighborhood operation	Geometric operation	Temporal operation
Brightness modification	Histogram equalization	Image smoothing	Display adjustment	Fame-based operations
Contrast enhancement	—	Image sharpening	Image wrapping	—
Negation and thresholding	—	—	Magnification and rotation	—

particular group among a number of possible object groups.

4. Industrial aplications

In order to describe the applications of machine vision systems; four categories of the visual inspection, process control, parts identification, and robotic guidance and control mechanisms are considered. In this field, the most significant task of the machine is for the automated visual inspections (AVIs). The main concern of using machine is to recognize that the part is well made according to the specified qualifications. AVI and parts identification do not contribute a significant role in the flexibility in manufacturing, however have considerable role in the automation task. On the other hand, vision systems in the process control and robotic guidance can play important role in achieving more flexibility in manufacturing [5,6].

4.1. Automated visual inspection

As described, the AVI does not enhance the flexibility of the manufacturing line because the only use of this system is for inspection, but the utilization of this system considerably enhances the automation capability of manufacturing process. The automated vision system can be used for the purpose of measurements, gauging, integrity checking, and quality control. In the area of measurements and gauging, the gauging of small gaps, measurements of the object dimension, alignment of the components, and the analysis of crack formation are common applications. Integrity checking in automotive plants, food industry and other production lines is performed by using such a vision system.

The medical and pharmacological products can be inspected by the machine vision systems. Using such an inspection method in the production line has increased the speed and reliability of the inspections. For example, during the automotive assembly, a vision guided robot recognizes the orientation of the engine heads and picks and places them correctly on the engine blocks [7]. In another case, a system examines the fiber optics assembly line. A PC-based imaging system integrates hardware and software to analyze the captured images for the possible fiber blemishes, chips, and cracks [8]. As an another example, in aerospace industry, a vision-based robot using the self-calibrating and self-teaching techniques has been reported that punches rivets into the airplane metal sheets with the high accuracy [9]. A list of possible applications of AVI for measurements and gauging and quality controls are given in Table 2.

4.2. Process control

Utilizing a vision system could help a better analysis, control, tracking, and the issuing documents in different applications. Applying vision system also can help the analysis of the nozzle-plates, and monitoring production process. It also provides on-line inspection and imaging options for the biomedical, pharmaceutical, metal finishing, lumber production, and also in the automotive production assembly lines. Successful operations of the vision system for the process control and tracking tasks are shown in Table 3.

4.3. Parts identification

Parts identification and classification are one of the most important applications of a vision system. Sorting of the automotive castings, parts, and identifying and unloading of parts from pallets are important applications. Sorting and grading of the food and other products are another example of such identification applications. Some typical applicational examples for the identification and classifications are listed in Table 4.

4.4. Robotic guidance and control

The automation process is based on the different robots, which require guiding systems. Alignment and adjustment processes also require smart guidance systems. In general, in the automotive plants guidance of the robotic action is performed by using the vision system as smart sensors for position determination in the welding or other processes. Table 5 gives a list of the possible applications of the vision system for the robot guidance and control.

5. Future developments

It is desirable to employ the automation technique to improve the manufacturing production lines and the resulting products with a high efficiency in order to stay alive in the competitive world market. In order to accomplish this automation in a more flexible manner, the feature of flexibility must be added to the automation as well. Thus, the automated flexible manufacturing is

Table 2
Possible operations for automated vision inspection

Measurement and gauging	Integrity checking and quality control
Gauging of spark plug gap	Automotive plants (enhances inspection of automobile parts, safety inspection of brake assemblies, valve spring, piston rings and rods, confirm switch integrity, Check auto axle assemblies, asses oil-seal surfaces, inspect truck beds, check laser welds, detects engine–fuel leakage)
Measurement of belt width	Food industry (classify fruits, grades moving products)
Measurement of tool wear	Checking correct printing pharmaceutical labels
Mark alignment and pick and place component offset	Paint finish assessment
Analysis of crack formation and propagation	Production lines (inspection of machined surfaces, roughness, flatness edge damage and nicks, inspect bares acrylic-sheet defects, , inspects indexable insets, cutting tools, real-time web-inspection system finds steel defect, steers package inspection, automates glass-machine-tool inspection, network cameras check components)
Calibration and inspection for automation	Electronic and electro-optic industry (inspection of printed circuit boards, microcircuits, fiber optics connectors, semiconductor inspection, elimination of surface defects in photographic film webs)
Robot and vision system assemble diagnostic devices, inspects and grades rough wooden boards	Medical and pharmaceutical plants (validates medical containers, inspect tubes for proper filling and sealing, ensures medical pill qualities, ensures product and packaging quality)

Table 3
Example applications of vision system for process control

Process control	
Speeds food processing and high-speed sorting	Applying vision to nozzle-plate analysis
Fiber analysis in the wood panel industry	Event-capture system monitor paper-making process for breaks and defects
Control of flatness in float-glass manufacturing	On-line inspection ensures needle quality
Checks display pixels	Imaging options from biomedical, pharmaceutical to metal finishing and lumber production
Shortens fiber-alignment time	Issuing documents (driver licenses, credit cards)
Tracks pill bottles CMOS, 3-D display offers crystal ball viewing,	Automates catheter manufacture Orients credit cards
Smart cameras check fast moving connector pins, smart sensors automatically perform multiple inspections of piston rings and rods	Robot/vision add flexibility to auto-part manufacturing (layered bin picking)
Tracks targets on missile flights (measuring the accuracy and the performance)	Inspection and alignment of wafers

recommended and flexibility is enhanced by building the programmability to the automation, interlinking machines and adapting the manufacturing process. The ultimate goal is that the production machine must be equipped with a vision system so that it can perceive changes to the products and its environment and then react accordingly. Also such a feature allows machine to accomplish hard tasks such as imaging the complicated assemblies. As a result, the vision-assisted automation can ensure that cost saving follows from benefits such as the reducing work in progress and the labor cost in the mass production scheme.

Table 4
Typical applications of vision system for part identification

Parts identification	
Sorting of automotive castings	Unloading materials from matrix packaging
Automobile well-to hob assembly	Identification of car bodies by outline
Automotive tyre-to-wheel assembly	Automatic decoration of chocolates
Precision application of car body seam-sealant	Sorting of fish by species, size determination and inspection
Unloading of automotive crankshafts from pallets	Machine vision and barcode inspection identify fast moving parcels
Identify license plate of moving vehicles	—

5.1. Development in image acquisition

One of the most important design parameters in developing a machine vision system is the most effective type of lighting, which depends on the light source and the related optics. Now the system integrators can select from a number of illumination technology such as the fiber optics,

Table 5
Typical applications of vision system in robot guidance and control

Guidance and control	
Automotive windscreen alignment and placement	High precession part-mating in aerospace applications
Seam location and following for welding car chassis members	Pattern-correct sewing in textile manufacture
Acquisition of cylindrical objects from the bin (bin picking)	Smart vehicles (imaging a target-rich environment)
Vision guided nuclear fuel sub-assembly dismantling	—

tungsten lamps, fluorescent, light-emitting diodes in a number of configurations. These configurations include the ringlight, spotlight, backlight, and diffuse light [10]. Light sources are able to enhance the imaging contrast. Proper light source helps discern imaging features for the machine–vision systems [11]. Multiple cameras are another feature that can be helpful in some cases. For instance, the machine vision system using this technique has been proposed to inspect the engine parts for defects [12]. One possible development in the area of vision hardware system is using the advanced laser scanning systems. For example, a proposed method of active triangulation such as the one described in Ref. [13]. The transmitting mirror, target and the receiving mirror forms a triangle. The scanning of the object is accomplished by rotating the transmitting mirror at a constant speed. The receiving mirror reflects beams through a focusing lens to a position sensitive photo-detector. A simple geometry for the usual triangulation method, in which a light beam originating from position d along x-axis is projected at an angle to provide a reference point ($d/2$, l) of the object for calibration purpose, is reported. The image of this point at the focal plane of a lens at the origin with focal length f is located at $-df/2(l-f)$ position on the detector plane. In this scheme, the detector is placed at the focal plane at $-fl/(l-f)$ along the z-axis.

The mathematical relation between the object coordinate (x,z) and the parameters of the geometry is given in Ref. [14]. Now if we add a scanner at the origin (0,0) that rotates synchronously with one at point (d,0), we can arrange the synchronous system. As can be seen, this has two effects: First, the position of the synchronized image p' is closer to the reference image point in comparison with the image p of the usual triangulation. Second, the rotation of this scanner at origin cancels the rotation of the first scanner and hence results in synchronization. In this case of the synchronized geometry, from 2-D object data we have only one image point, which is beneficial from detecting point of view. To acquire 3-D information, one can use a bidimensional scanning method as described in Ref. [15]. In this way, a dual–axis synchronization scanning geometry is arranged in which θ is the scanning angle in xz-plane and ϕ is the scanning angle in the yz-plane.

By trigonometry, we have calculated the image point coordinate (X,Y,Z) and the parameters of the scanning geometry that is derived in Ref. [15]. Another proposed geometry is the one in which the object rotation is performed. The 3-D image point coordinates can be obtained again by trigonometry relation [15]. In this type of scanner, the polygonal scanner can provide the scanning in the ϕ direction. Now by using the described geometries in combination with an appropriate photosensitive detector, a 3-D camera vision system can be established. It is possible to use the CCD, diode arrays, bicell, or even a single detector for image acquisition. The scanning geometries described here could therefore lead to realization of low-cost 3-D camera because; it is possible to use a low cost photosensitive detector rather than the CCD camera system. Design and construction of such a system together with some of the results are presented in the previous report [15]. We have used this device for detecting range data and the results of scanning a cylindrical surface are given there. The results show that the reported system can be used, as a range finder, and also as a two-dimensional scanner for obtaining the three-dimensional data required for a laser based camera system.

Another possibility is to use the X-ray or infrared lighting, which offers some advantages. For example, the machine vision and infrared lighting technique has been used to track the production quantities, detect defects, and screening problems. The infrared spotlight is employed to detect and inspect the glass-bottle flaws [16]. X-ray technology machine vision system has been proposed for the inspection of the air-bag inflators [17]. High-quality machine vision system should integrate an image acquisition subsystem that produces a high-resolution pictures (512×512 pixels). Such devices offer significant advantage to acquire the precise information about relative positions of several objects within a scene in a single glance.

5.2. Development in manufacturing process

The ways that an industrial process can be justified depends on the type of applications, however; in general, improvements must be made in the safety and reliability of the manufacturing process, in product quality, and enabling technology for a new production process at a minimum cost. In all mentioned processes, the integration of a correct vision system can play an important role. Such developed vision systems can offer a way to perform the 100% inspection in order to improve the safety of the process and also the reliability of the manufacturing process. Examples are useful for the aerospace and the defense industries, which require a critical safety status. In the automotive and other industries improved vision system using proper lighting can be helpful to achieve the cost-effective and reliable 100% inspection for the assembly lines. Beside the fact that a machine vision system can fulfill important inspection function as described, these machines also can be used to increase the degree of the flexibility of the manufacturing processes. The importance of such a parameter is given in a report by Bessant and Heywood [18].

The degree of defining flexibility in the manufacturing process is given by Bessant in which the variability in products is presented as the scale of production. As one increases the scale of production a more dedicated automation in the mass production is requires. On the other hand, any increase in the variety of products requires the specialist skilled workers in very small batch production. Now flexible manufacturing provides a means to optimize the interrelation between these two processes. Input parameters required for such advanced manufacturing that increases the flexibility factor, includes the new technology and methodology. The technology consists of the DNC, automated vehicle guided system (AGVs), robotics, computers, etc., and the new methodology considers the adoption of just in time (JIT), quality control, group technology, value analysis, etc.

6. Key points in design and applications

Different aspects of a machine vision system are shown in Fig. 2. As can be noticed in Fig. 2, it includes the scene consideration, image acquisition, image pre-processing and post processing. In any optimal design, one must consider the systematic consideration and machine vision justification for any application. Image acquisition is one of the most important processes for the performance of a machine vision system, because with a high-quality image in hand the following processing and analysis of the image would be easily feasible. Both the hardware and software are involved in this process and the selection of proper components is crucial to image acquisition process. In general, two method of active and passive can be used to record an image. In the first method, a light source is used for the object illumination while in the later one, the sun light is used for the illumination purpose. For the production lines and the industrial applications, the active method is more suitable and therefore the choice of the light source is an important factor. Depending on the type of the applications lamps, LED, and laser sources can be employed. The wavelength of the electromagnetic wave is also important in the image recoding and the visible, IR, or X-ray region of the spectrum can be used for the scene illumination. Incoherent light sources are less expensive while the coherent laser light sources are more expensive and considered as specialized light sources for the specific imaging consideration.

Image capturing method is another point of consideration and the single, stereo, and multiple camera can be utilized for image taking. The specification of the light illumination is also important in lighting condition. For example, the shadow, diffuse or other methods can be used for object illumination by using the point, or strip light arrangements. To record the image, a sensitive photo

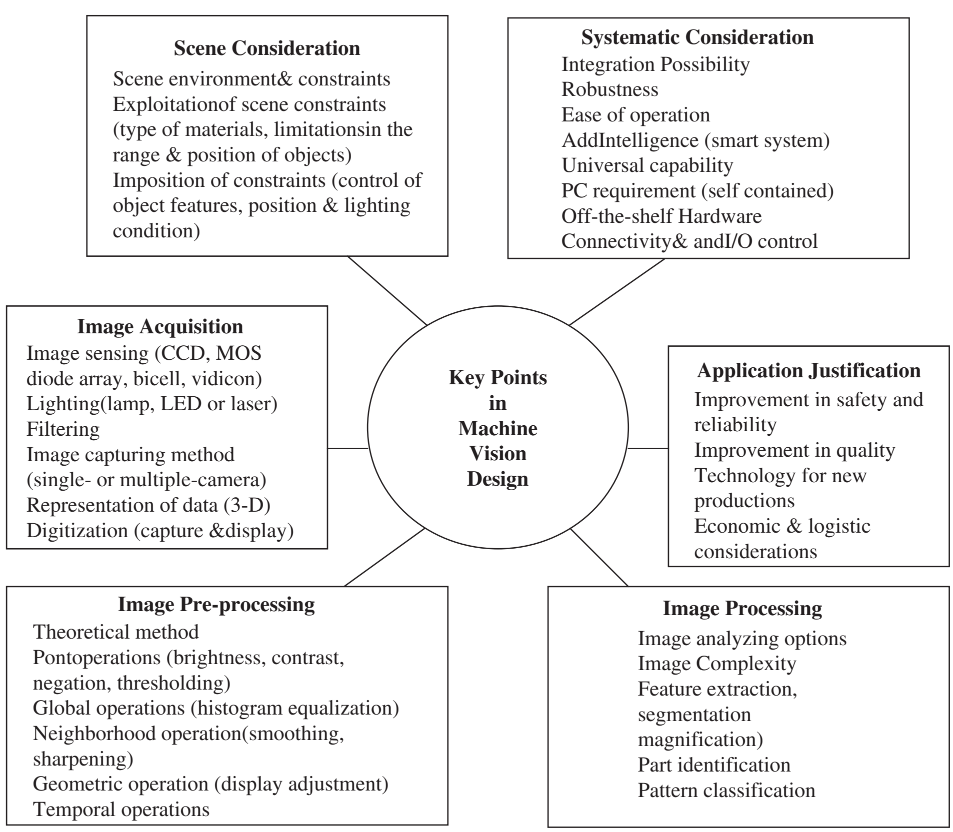

Fig. 2. Key points in design and application of a machine vision system.

detector is required in order to obtain the optical image. The optical signal is converted by such a detector into an electrical signal. The type and characteristics of the photodetector is really important in the quality of the captured image. The single-photo diode, by-cell, diode-array, CMOS detector, and vidicon can be used for light detection. Capture and representation of data are important in image acquisition. Digitization and display of the image are other factors that must be considered in the selection of the components, methods, and software. With the importance of the digital signal processing, digitization is an important factor.

The key points in a machine vision design can be generally classified into the six different categories such as: the scene constraints, image acquisition, image pre-processing, image processing, machine vision justification, and finally systematic considerations. A scene for example can be an industrial site in which a production line, process or machine specifications can be imaged. Thus the scene specifications, environment, and all the constraints must be considered in the design. The assembly line, size and type of imaging objects or object groups must be considered in the machine vision design and operation. The crucial point is that the machine vision system should be able to operate efficiently even for the case of the randomly-oriented object scene and be able to produce a clear image of the small objects occluded among an object group. Types of materials, limitations in the range and positions of the objects are important in this respect. Imposition of such constraints in the design and operation of a machine vision system is also important factors. According to the given conditions for any scene, the control of object feature, position of the object, and the lighting condition must be selected properly.

7. Summary

A general-purpose machine vision system with its industrial applications was described. Such a machine must be flexible in the scene so that it would be able to operate in virtually unconstrained environments containing ill-defined objects, which partially occlude one another. The first generation vision system (early 1970) incorporated the 2-D acquisition and the second-generation incorporated the 3-D acquisition and processing capability. In our opinion, the next generation vision system should implement laser source light, in particular semiconductor lasers, in order to improve the quality of the captured images [19]. Physical properties of the laser scanning system should provide, polarization, and intensity distribution in order to obtain special images for more complicated cases. As mentioned, the brightness of the picture is important issue while the state of polarization and interference effect can lead to a new kind of holographic images. Thus the image analysis description of the 2-D relationship must be enriched and extended to include the 3-D relationship between objects within a real-world scene. The next generation should lead towards the machine vision systems with the universal capabilities to provide the 3-D description of the scene. Required characteristics for such a machine vision system to meet the universal standard conditions and capabilities are listed in Table 6.

In the design and operation of a vision system, the image formation and visual process, computational methods and algorithms, depth information, image representation, and modeling and matching must be considered. On the other hand, the systematic consideration is important in the efficiency and the performance of the selected machine. The integration possibility, robustness, ease of operation, and adding intelligence into the system in order to make it a smart system are features of the advanced machine vision systems. The universal capability, PC requirement (self contained), off-the-shelf hardware, connectivity and I/O control options are the key factors in this respect. For any production line and manufacture plant, there should be a good reasoning for utilizing such a machine vision system. Improvement in safety and reliability of the products, improvement in the quality, and the introduction and possibility of a technology for new productions are key points in the support of the machine vision system. The economic and logistic considerations are also crucial factors, which justifies the utilization of a machine vision system.

In the final words, the new generation machine visions must satisfy the two key points: the first is the determination of a better geometric correspondence between the points in the scene and the points in the captured image. That means a proper choice of the algorithms and computational methods and proper implementation of physical parameters to map the image points into that of

Table 6
Characteristics involved in the design of a universal machine vision system

Image formation and visual process	Computational process	Depth information	Image representation	Modeling and matching
Monocular	Algorithms	From stereo	Generalized cylinder	2D Modeling and matching
Binocular	Theory Marr's Theory	From texture	Volumetric elements	3D Modeling and matching to 2-D image data
Visual perception	Implementation	From shading	Surface representation	3-D Scene description
—	—	—	Wire-frame representation	—

the object points. The second point is the precise determination of brightness at the resulting point in the image, representation of the image, and extraction of features in a detailed image. The first improvement requires development of the better computational methods while the second point implies the systematic developments. One suggestion is the use of the coherence characteristics of the laser source light instead of the conventional lamps together with the special optics in order to obtain the high-quality images with the high pixel resolutions.

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