

Principle and Applications of Retroreflective Vision Sensing for Discrete Part-Presentation

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For flexible manufacturing of short production runs where a large variety of product sizes, component types, and surface reflectance characteristics are encountered, it is desirable to build flexible computer-controlled systems for feeding parts into machine tools or assembly processes that combine maximum flexibility and reliability with minimum cost and cycle-time. This is not a general bin-picking problem; the parts are assumed to be prepositioned approximately in totes/pallets/kits with regularly spaced locations. This article presents a machine vision technique based on the principle of retroreflective vision sensing for part-presentation. Since retroreflective material has a distinctive surface reflectance that is not commonly found in natural or man-made objects, the use of retroreflective surfaces enables reliable high object-to-background contrast images to be obtained for a wide variety of objects. Unlike conventional machine vision techniques, which rely on the variance of the surface reflectance of the objects to generate detailed images, retroreflective vision sensing aims at generating a reliable two-dimensional digital object silhouettes so that the location and orientation of the part can be reliably determined. Two application examples, machine loading and assembly, are illustrated.

短期間の柔軟性を持った製品の製造では、非常に多彩な製品サイズ、構成、表面の性質に遭遇するので、最小限の費用と時間で最大の柔軟性と信頼性を兼ね合わせた、機械工具や組立工程に部品を供給するための柔軟性を持ったコンピュータ制御システムの構築が求められる。これは一般的な箱を持ち上げるような問題とは異なり、部品は予め規則正しく収納器、パレット及びキットの中に配置されていることが前提となっている。この論文では、それらの部分認識のためのretroreflective vision sensingの原理に基づいた機械による認識技術について説明している。

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逆反射性の素材は、一般に見られる自然界や人間が作った物体とその表面の反射特性が異なり、逆反射性の表面を使うことで、非常に多くの物体に対して物体と背景のハイ・コントラストの信頼性の高い画像が得られる。従来の機械による認識技術とは違い、この手法では物体表面の反射特性の違いを利用して詳細な画像を得おり、retroreflective vision sensingは信頼できる2次元のデジタル化された物体のシルエットを作成することを目的とし、対象となる部分の位置と運動方向は確実に決定出来る。機械による積み降ろしと製品組立の二つの応用例が解説されている。

INTRODUCTION

The rapid advancement of robotic technologies which offer relatively high performance at reasonably low cost has greatly accelerated the trend of using flexible automation to maintain consistency in product quality and to ensure human safety by avoiding direct human interaction. One of the most important functions of industrial robots is feeding discrete parts for machine loading and assembly processes. For flexible manufacturing where a large variety of product sizes, component types, and surface reflectance characteristics are encountered, the robotic part-feeding system must have the ability to adapt to a changing product design without costly hardware redesign or time-consuming software reengineering. This has been treated as a general bin-picking problem by several authors, but often the parts are in separate, regularly spaced locations in totes, pallets, or kits. In these cases the part location is approximately known, and the problem is to precisely locate known objects.

A typical automated machine cell or workstation consists of a robot, an end-of-arm tooling section, a part-presentation system, and the machine tool or assembly cell. The most common approach for presenting parts to a completely preprogrammed robot is to use specially designed pallets for each part family and rely on the pallet to maintain sufficient positional accuracy. For small batch production, success is achieved at the expense of high operational cost and lack of flexibility. The high operational cost includes excessive packaging costs for transport, precise alignment of the pallet, hardware redesign, and fabrication, and disposal of the pallet. It is more desirable to have parts presented to the manipulator in individual bins in low-cost dunnage trays or reusable egg-crate style pallets which do not have to maintain the part's positional accuracy. Furthermore, it is essential that the flexibility gained in any alternative part-presentation system must be cost-effective, i.e., it must require relatively little cycle-time, short or zero set-up time, and not sacrifice reliability.

Significant research efforts have been directed towards the use of machine vision for object identification. The conventional machine vision techniques generally rely on the design of lighting systems.¹⁻⁴ Most of the literature on structured illumination systems for flexible manufacturing whether they use dark-field or bright-field illumination, is based on techniques which require a prior knowledge of the object geometry and surface reflectance. Although illu-

mination techniques have proven useful for automating product inspection, these have been found in practice to be too expensive, less flexible, and less reliable than required for on-line real-time part-presentation. Moderate location inaccuracies pose no difficulty for human operators since they use vision, hand-eye coordination, and a sense of touch to locate and correctly load the part. The attempt to duplicate human perception by obtaining a three-dimensional detailed image of the part often calls for time-consuming computation and does not necessarily determine the location and orientation of a given part with the accuracy required for successful part-acquisition by the robot.

This article outlines a computer vision technique for generic part-presentation using structured surface reflectance rather than object-dependent structured lighting. Structured surface reflectance can be created using retroreflective materials⁵ on (1) generic part-feeder surfaces so that the part appears as a uniformly dark image on brightly illuminated background or on (2) the part to serve as retroreflective landmarks against a virtually dark background. The reflected light from a retroreflective surface is returned in a direction close to the direction from which it came over wide variations of the incident angle. Since the retroreflective property is not commonly found in general objects, the combination of retroreflector and illumination produces a high contrast image. Retroreflective materials have been widely used in traffic control and safety signs on highways and in airports.⁶ Incidentally, the retroreflector has also been used as a noncontact position sensor for a large space structure⁷ and more recently, in field tracking of automated guided vehicles (AGV).⁸ Unlike the above cited applications where retroreflective surfaces are used primarily in tracking well-defined landmarks, this article establishes the basis of the design concept needed for generic part-presentation using structured retroreflector and illumination in a part handling problem. The technique does not rely on a knowledge of the reflectance properties of the parts to be handled. The retroreflective vision sensing described in this article aims at generating reliable digital images so that the location/orientation of parts can be determined accurately with relatively simple, high-speed computation, and without the need for a detailed reflectance map.

The remainder of this article is organized as follows. The second section discusses the design principles of generic part-presentation. The third section addresses the factors which influence system performance. The collocated illumination technique for a retroreflective part-feeder is presented in the fourth section. Two industrial application examples are illustrated next followed with a general discussion and conclusion.

GENERIC PART-PRESENTATION

A typical workcell of an automated factory consists of a robot, a part-feeder, an end-of-arm tooling section, and the manufacturing process. The parts with "one-side-up" are contained in a pallet, which may be transported by means of an automated guided vehicle (AGV) or a conveyor to the loading tables. The location and orientation of a given part are determined using simple machine

vision, which are then presented to the robot controller for feeding the part to the machine process.

Part Presentation

Since the gripping configuration of a given part is generally process- and object-dependent, it is assumed to be predetermined off-line with respect to a body frame attached at the part centroid and a characteristic direction of the part such as one along the principle axis of the least second moment of the two-dimensional image. If a two-dimensional digital image is taken on-line for each of the workpieces to be grasped using a simple machine vision camera mounted on the robotic arm, the centroid and the characteristic direction of the part can be determined with respect to a known world coordinate frame from the digital image. Since the centroid and the characteristic direction have been uniquely determined with respect to both the gripper coordinate frame off-line and the known world coordinate frame on-line, the gripper frame with respect to the world coordinate frame can be computed and presented to the robot controller to allow feeding of parts to the subsequent processes.

The geometric properties of interest, namely the centroid and the characteristic direction, can be computed from an appropriate two-dimensional image of the given part characterized by high object-to-background contrast without the need for detailed geometry. Since the two-dimensional image presents only the outline or silhouette of the object, it is a great deal easier to store and to process and lends itself to high-speed hardware implementation. The generation of the object silhouette, however, requires an essentially two-dimensional pattern of high object-to-background contrast. The vision-guided part-presentation discussed in this article aims at generating reliable two-dimensional digital images so that the location and orientation of a given part can be determined. The vision sensing technique is "generic" since it does not require a prior knowledge of detailed object geometry or surface reflectance.

Retroreflective Vision Sensing

The two most common types of surface reflectors found on object surfaces are diffuse and specular as shown in Figure 1. An ideal diffuser is one that appears equally bright from all viewing directions and reflects all incident light, absorbing none. Surfaces covered with papers and matte paints may be considered as reasonable approximations. An ideal specular reflector is one which reflects all incident light into the same place as the incident ray and the surface normal. The emittance angle between the reflected ray and the normal equals the incident angle between the normal and the incident ray. The third reflectance known as retroreflector is not commonly found on the surfaces of general objects. The retroreflector returns most of the radiation in the directions close to the direction from which it came and this characteristic is maintained over a wide variation of the angle made by the incident light ray and the normal to the retroreflective surface.

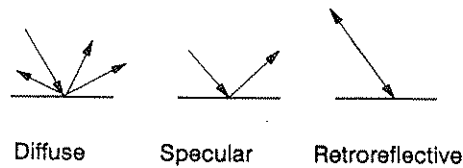


Figure 1. Types of optical surface reflection.

Figure 2 shows the nomenclature used in standard measurement of retroreflective materials,⁵ where the observation axis is perpendicular to the object plane. The typical observation angle curve and entrance angle curve for a high intensity retroreflective material called Scotchlite⁹ is displayed in Figure 3. Within an angle of 0.2 degrees from the principle axis of incident light, the light intensity of the reflection from Scotchlite is 250 times greater than that reflected from a flat white surface. It is so highly reflective that images of other objects in the field of view can be virtually eliminated by using a strobe near the photoreceptor and short exposure times. The basic principle of the retroreflective vision sensing is to structure the surface reflectance of the pallet so that it is much brighter than object generally characterized by diffuse or specular surfaces. In practice, the picture cells corresponding to the object will not all have repeatable or uniform gray-level. Thus, a number of nonpredicable factors such as measurement noise, the uniformity of the surface reflectivity, and the uniformity of illumination, which occur on both the object and the background, can be eliminated by a relatively simple technique. If the retroreflective material is applied on the surface of the pallet as illustrated in Figure 4(a), the object appears as a dark silhouette against a reliable bright-field background since most of the incident illuminance from the object is reflected or diffused away from the aperture whereas that on the pallet surface is retroreflected.

Alternatively, brightly illuminated retroreflective landmarks can be intentionally created on objects for location tracking as illustrated in Figure 4(b).

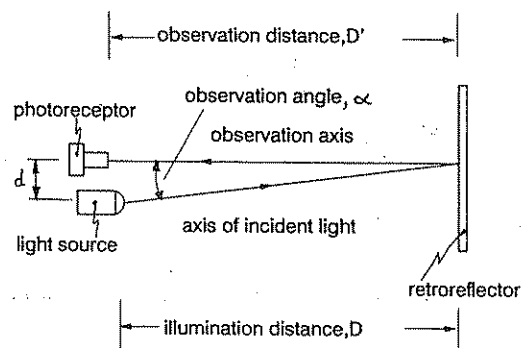


Figure 2. Nomenclature for retroreflective measurements.⁵

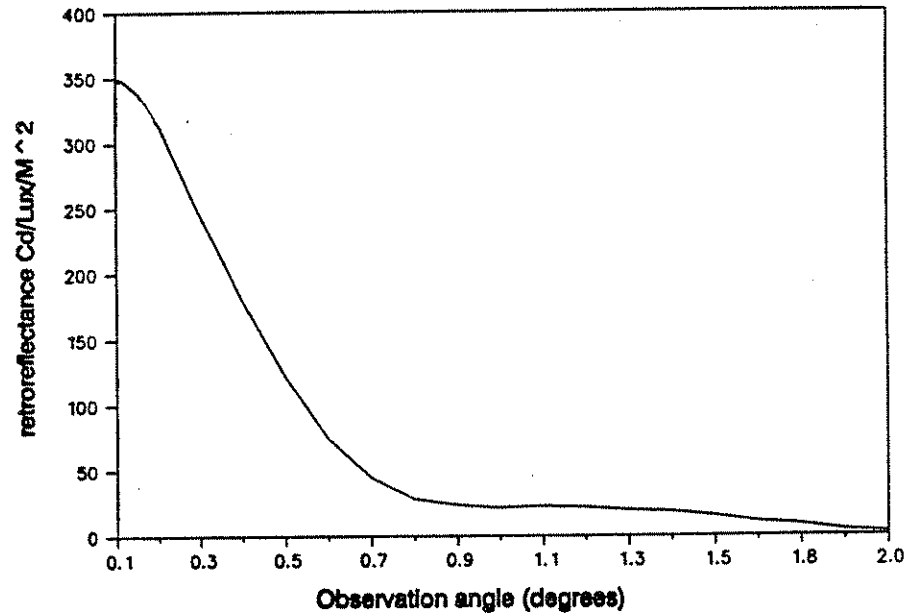


Figure 3(a). Response of scotchlite retroreflective materials.

SYSTEM DESIGN CONSIDERATIONS

Three design factors which strongly influence the generic feeder design and collocated illumination using the retroreflectors are (1) the small observation angle, (2) the reflection of ambient lighting, and (3) the reflection from parts



Figure 3(b). Coefficient of retroreflection.

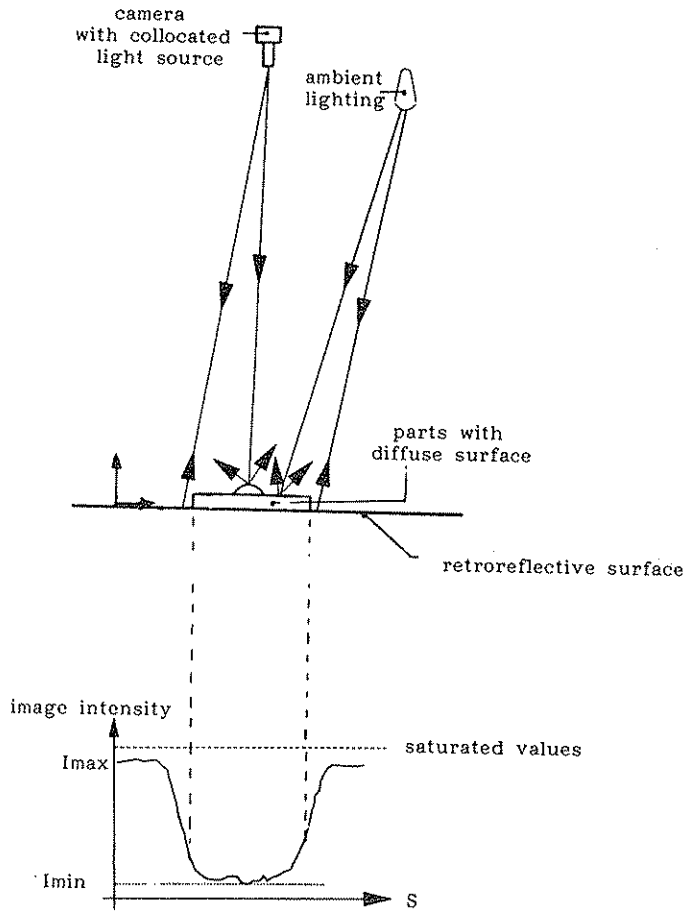


Figure 4(a). Structured retroreflective background.

with specular surfaces. As shown in Figure 2, the lateral distance d from the center of the entrance aperture of the camera to the axis of the incident light, measured perpendicularly to the observation axis can be computed by

$$d = D' \tan \alpha$$

where D' is the observation distance and α is the observation angle. In order to achieve high object-to-background contrast, the entrance aperture of the camera should be placed as close to the strobe as possible to receive most of the reflected light from the retroreflector. For the general landmark tracking applications such as highway traffic control, field tracking of large space structures, and AGV guidance the observation distance is relatively large, which allows the use of a separate illumination source. However, the range of observation distance commonly encountered in automated part-feeding, which is typically 1

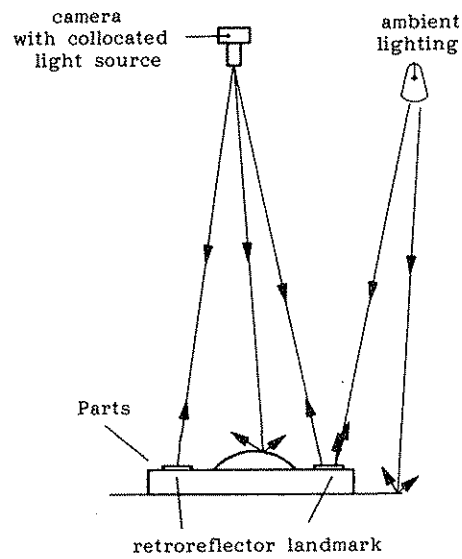


Figure 4(b). Engineered object "landmarks."

meter or less, requires the illumination source be integral to the camera body for effective retroreflection.

Specular objects such as polished steel reflect a large proportion of light from any illumination sources. As illustrated in Figure 5, the reflected light from the

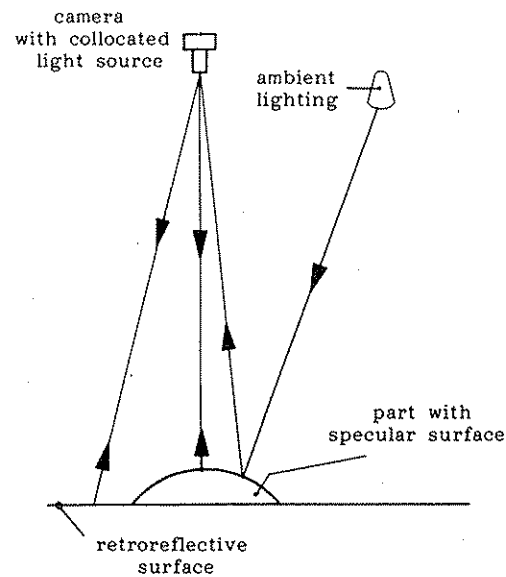


Figure 5. Effect of ambient lighting on specular surface.

ambient lighting and the collocated illumination tends to contaminate the silhouette of the specular object, which otherwise appears dark in the image. The ability to reduce the contamination due to the reflection from the specular surfaces has a significant effect on the system reliability. In general, the degree of contaminations depends on the object reflectance and geometry as well as on the entrance angle, the surface area of the illuminator, and the relative luminous intensity of the illumination system. It is desired that the illumination for the retroreflector should be designed without altering the existing lighting layout for the general illumination of the factory.

IMPLEMENTATION TECHNIQUES

In order to obtain a reliable image of high object-to-background contrast, it is desired that the photodetector responds only to the illumination from the collocated source structured for the retroreflection but not that of ambient lighting. If the detector is operated within the linear range of response to light intensity, the reflection from the ambient lighting can be eliminated by using the difference between two images obtained from the same scene, of which one is obtained with the other without the retroreflector illumination. This strategy, which needs no extra hardware requires, however, storage of two images and a significant increase of processing time. For applications where short cycle time is of particular concern, a general spectral illumination technique structured for a retroreflective part-feeder is developed to minimize the influence of the undesired specular reflection without altering an existing factory illumination layout.

Spectral Characteristics

The collocated source for the retroreflector has a spectral characteristic which is distinctive from the general lighting and is optimal to the photodetector response. The relative responses of the two most commonly used camera imaging sensors, namely, Charge-Coupled Device (CCD)¹ and Charge Injection Device (CID),¹⁰ are shown in Figure 6. The CCD is responsive to wavelengths of light from below 350 nm (ultraviolet) to 1100 nm (near infrared) and has a peak response approximately at 800 nm. The CID offers a similar spectral

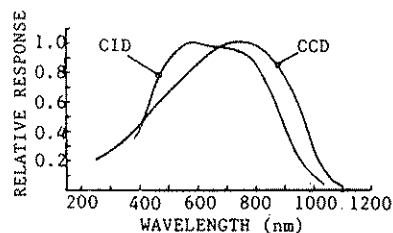


Figure 6. Spectral characteristics of CCD and CID devices.

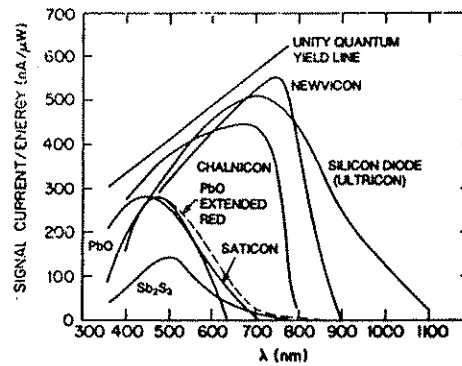


Figure 7. Spectral responses of various photoconductors.

response and has a peak spectral response about 650 nm. The relative response of vidicon camera,¹¹ however, depends significantly on the materials as shown in Figure 7.

Depending on the spectral emissions of illumination sources used as general lighting in factory environment, the influence of the ambient lighting can be effectively minimized or eliminated by means of spectral filtering. Gas discharge lamps generally have relatively high emission in the visible range and have little or no emission for wavelengths larger than 800 nm. The sun, tungsten lamps, and quartz-halogen type lamps have a wide spectral emissions. The spectral characteristics of three different spectral sources, namely laser diodes, LED lamps, and Xenon strobes, are of particular interest since the spectral wavelengths of these sources match the optimal response of the CCD and/or CID detectors. Pulsed GaAIAs Laser diodes¹² emit single frequency power in the 790–850 nm wavelength range. The irradiance at spectral wavelength in the range of 810–830 nm can also be produced from a Xenon lamp. AlGaAs LED, which is designed to concentrate the luminous flux into a narrow radiation pattern to achieve high intensity, has a narrow peak intensity at approximately 650 nm. A comparison of these sources is given in Table I.

Spectral Selective Illumination

A typical sensor/illumination system for a retroreflective part-feeder consists of a camera imaging sensor, a spectral filter, and a spectral illuminator. The constraint imposed by the small lateral distance d limits the physical design and the heat generation of the illuminator. Unlike the general purpose light sources which have a wide angular range of illuminance for uniform lighting on factory floor, the illuminator for the retroreflector should have a relatively narrow angular range of illuminance, generally no more than that required for the field-of-view (FOV). High illumination efficiency and thus low heat generation for a given brightness can be obtained. Three possible illumination designs which satisfy the requirements of small lateral displacement, narrow angular range of

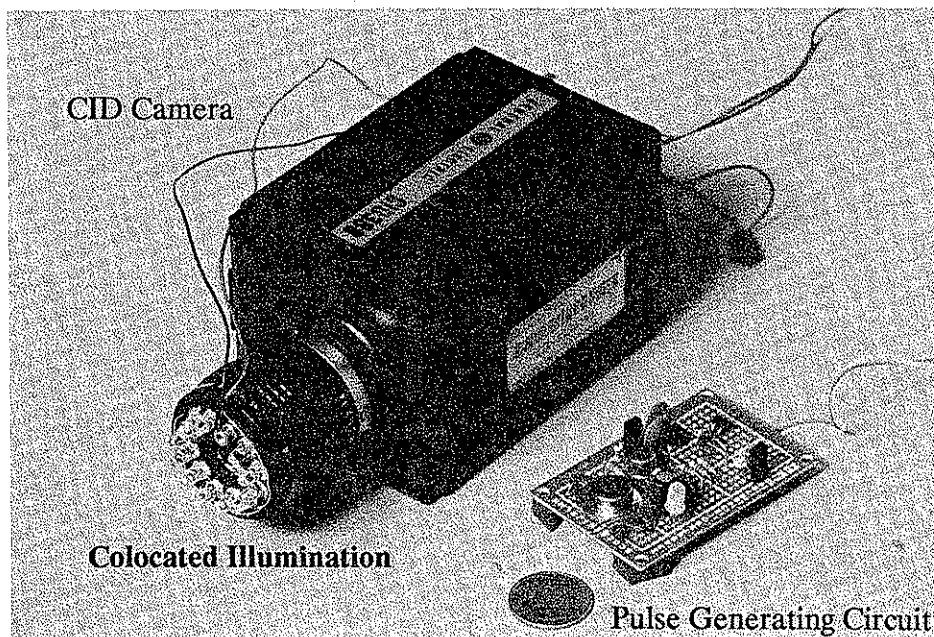
Table 1. Comparison between three spectral light sources.

Source	Wavelength (nm)	Unit Cost (\$)	Life	Power
LED lamps	570–630	1.00	5,000,000 hours (MTBF)	100 mW
Laser Diode	790–840	200.00	250,000 hours (MTTF)	1 W (peak pulse power)
Xenon flashtubes	830–1000	10.00	1,000,000 flashes (0.3–4 flashes/s)	25 W (500 V nominal)

illuminance, low heat generation, and high overall illumination efficiency are (1) the use of a single miniature high intensity point-source such as pulsed laser diode, (2) the combination of a beam splitter with an intense strobe, and (3) a ring-light of pulsed LED lamps or fiber-optic light-guide (as seen in Figure 8). All of these illuminators have a small light emitting surface area. The small area is important to (1) minimize the area of any specular reflection and (2) reduce the effective observation angle for retroreflective surfaces.

ILLUSTRATIVE APPLICATION EXAMPLES

The concept of retroreflective vision sensing was demonstrated using a commercially available camera and an illumination system as shown in Figure 8.

**Figure 8.** CID camera and structured illumination system.

The General Electric TN2700 CID camera (currently manufactured by CID Technologies) was used in this investigation. The CID camera has $484V \times 377H$ active elements and pixel size of $13.6 \mu m \times 23.4 \mu m$. Twelve HP4101 AlGaAs LED lamps (100 mW each)¹³ are evenly spaced at a 25.4 mm (1 in.) diameter from the center of the 16 mm C-mount lens. The number of LED lamps was limited to 12 by the requirements of small d , the type of lens, and the specified FOV. The LED lamps are chosen not only to match the spectral characteristics of the CID camera, but also because of the low cost, low power consumption, and long life span. The pulse-generating electronic circuit is to obtain high intensity light and to synchronize with the camera at a pulse width of 5 ms and a period of 16.6 ms. The observation distance is approximately 1 meter. The Data Translation frame grabber board DT 2803 was used to process the RS-170 image and to display the digital image on a Sony KV-1311CR color TV monitor. Two particular applications of part-presentation, namely machine loading and assembly processes, are chosen to demonstrate the concept feasibility, the implementation, and the illustrative applications.

Example 1—Machine Loading

Machine components are often fabricated from raw materials which may be precast, predrawn, or preformed to meet a certain specification. The components are generally required to undergo a series of machining processes and surface treatments prior to product assembly. The surface reflectance of the components ranges from “dull” to near “mirror-like finish” in a typical component fabrication. Common reusable pallets are used to house the components for several different machine processes. Figure 9(a) shows two typical machine

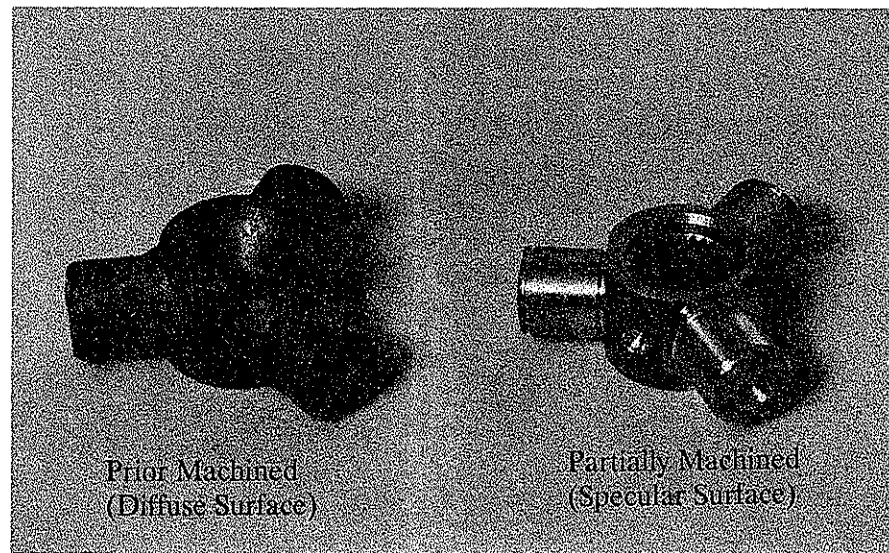


Figure 9(a). Typical machine components.

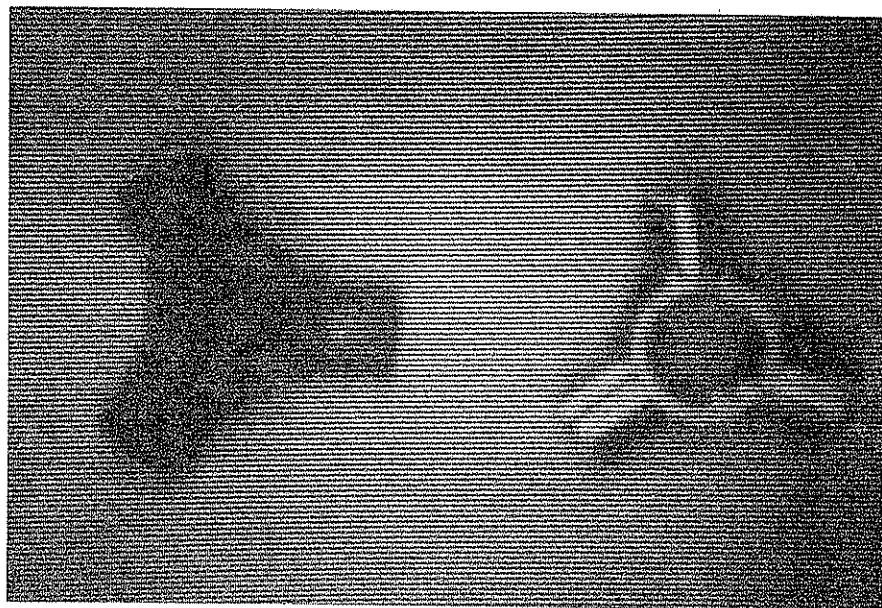


Figure 9(b). Conventional image of machine components.

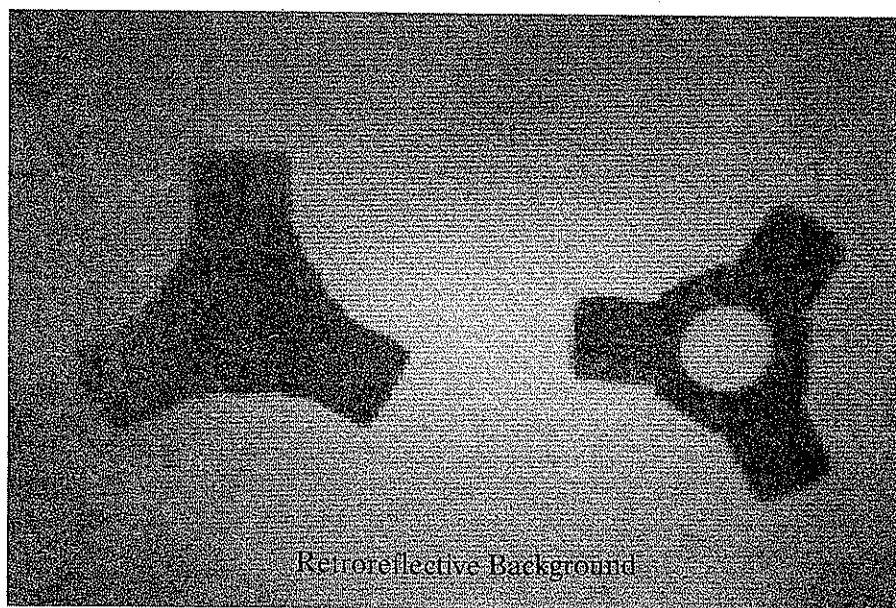


Figure 9(c). Retroreflective image of machine components.

components to be presented for machine loading. The object on the left is a typical component prior to machine processing, the surface reflectance of which is “dull” or diffuse. The object on the right is a partially machined component of the same type, which has several “mirror-like” machined surfaces.

A conventional digital image which was generated with no structured retroreflective background and with no illumination from the LED lamps is illustrated in Figure 9(b). Unlike the image of the diffuse surface on the left, the clarity of the two-dimensional projection is contaminated by the specular reflection which depends significantly on the layout of the ambient and/or the structured lighting. Figure 9(c) displays the digital images of the two components generated using the retroreflective vision sensing technique. A distinct silhouette of both the prior and the partially machined components can be obtained with a retroreflective background illuminated by structured LED lamps. Due to the highly intensive retroreflectance, the retroreflective vision sensing technique allows low-power spectral sources to be used to faithfully produce a high object-to-background image for location and orientation computation.

Example 2—Assembly Processes

Parts are often transported without maintaining sufficient dimensional accuracy to permit loading for subsequent assembly processes by a totally preprogrammed robot. Often the parts are prepositioned approximately in low-cost totes/pallets/kits with regularly spaced locations. To maintain sufficient positional accuracy in transport would often require excessive packaging costs and result in a lack of flexibility. Figure 10(a) shows a typical low-cost thin plastic tray commonly used to transport parts for assembly processes. The tray has partially diffuse and partially specular surfaces due to the irregularities of the geometry. The concept of engineered “landmarks” is illustrated in Figure 10(b). These landmarks can be used liberally in an engineered solution much as bar code labels are used to identify a part. The landmarks can be intentionally created. Alternatively, they can be obtained by modifying an existing label on the part as shown in Figure 10(b) where retroreflective material is used to produce the illustrative labels.

Figure 10(c) shows a conventional digital image of two switces on the low-cost tray, which was taken with no illumination from the LED lamps. The clarity of the two-dimensional image relies on the object and background surface reflectances. There are two problems in determining the part location and orientation from the two-dimensional image in Figure 10(c). The first problem is the poor contrast between the part and the tray. The second problem is created by the confusion caused by the specular reflection of the irregularities of the tray surface geometry. To avoid specially designing the tray to match the specific part, the concept of engineered “landmarks” as illustrated in Figure 10(b) can be used. Figure 10(d) displays the image generated from the same scene but with the landmarks illuminated by low-power LED lamps. Using the retroreflective vision sensing technique, the landmarks were faithfully repro-

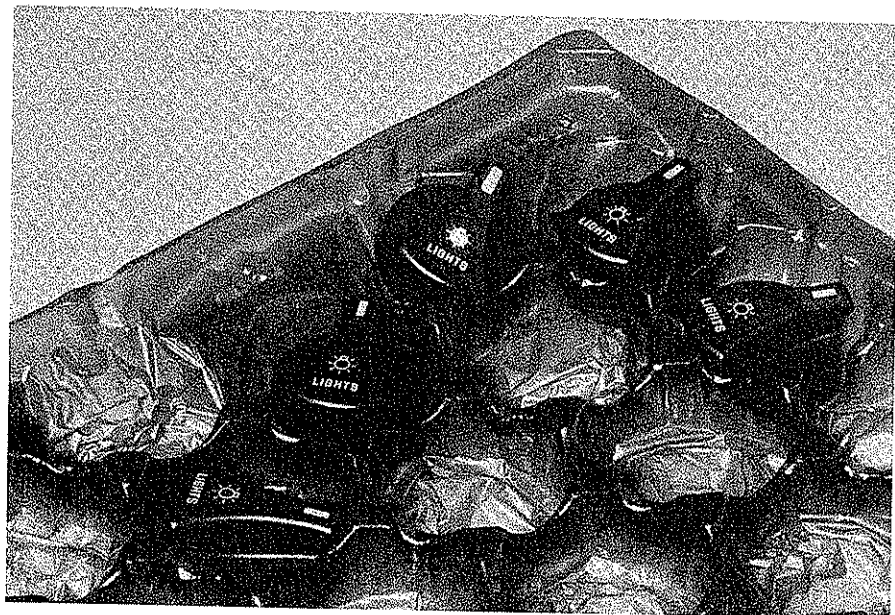


Figure 10(a). Typical low-cost tray.

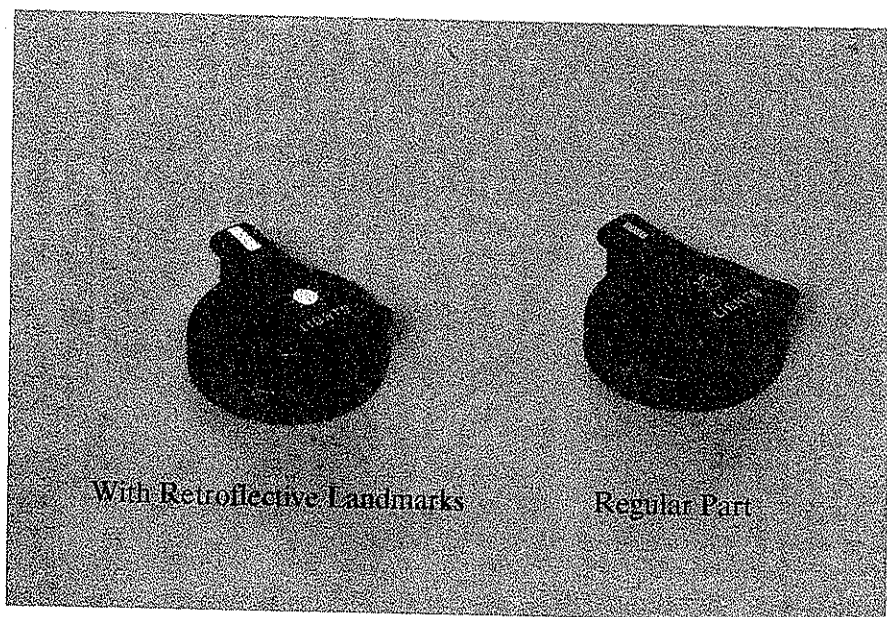


Figure 10(b). Illustrative engineered "landmarks."

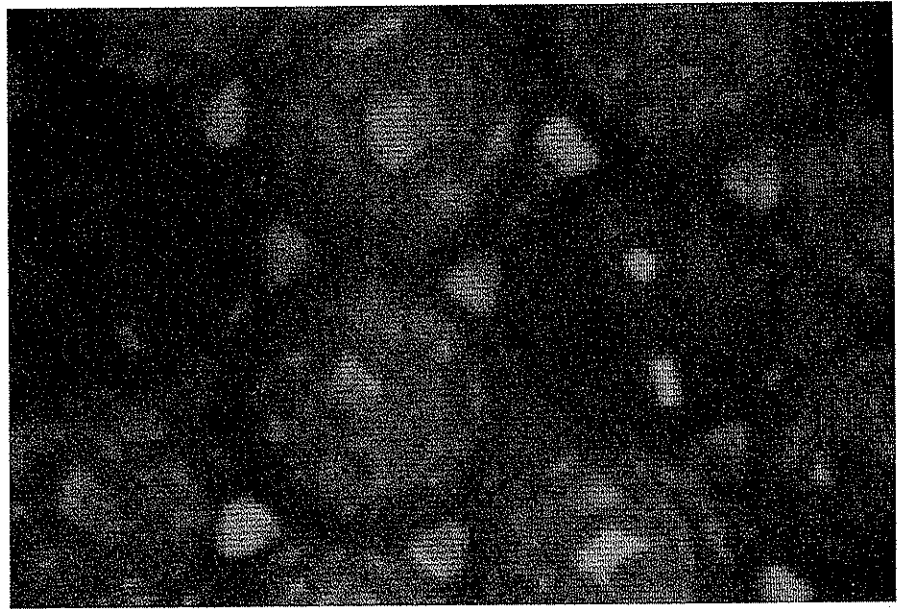


Figure 10(c). Conventional image of parts.

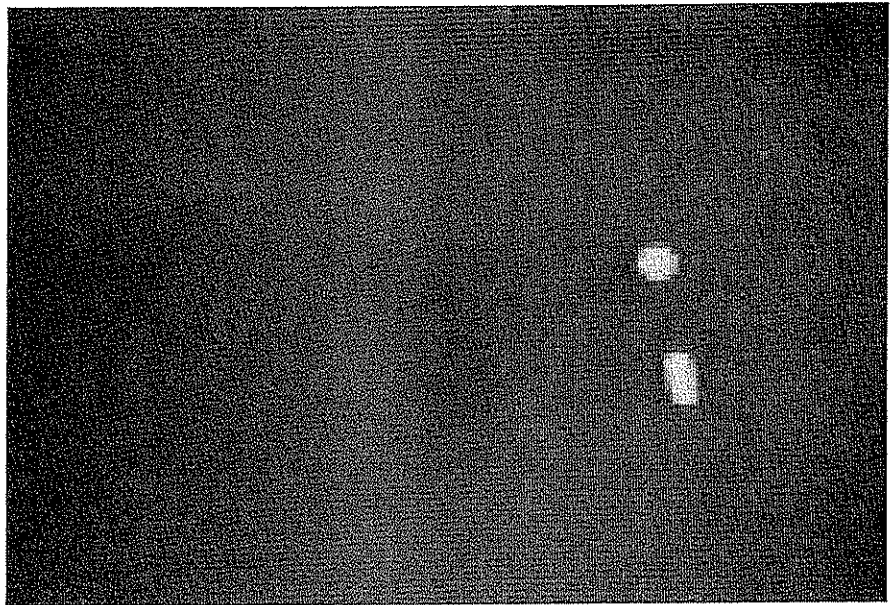


Figure 10(d). Image of retroreflective "landmarks."

duced against the virtually dark background and the irregularities of the specular reflection have been completely eliminated. The relatively simple image of the landmarks allows high-speed computation of the location/orientation to be made.

Application Considerations

Retroreflective materials can be used as a background in generic part-presentation or as a landmark on parts. The choice clearly depends on the part design and manufacturing process as illustrated in the previous two subsections.

When retroreflective materials are used as a background in generic part-feeders, the location and orientation of the parts can be computed from the two-dimensional object silhouette. The use of retroreflective materials does not introduce any new limitation to the two-dimensional part recognition problem. This approach, however, is limited to applications which meet the following requirements: (1) It is necessary that the required orientation of the parts can be characterized by the two-dimensional object silhouette; (2) The thickness or the depth of the parts should be small compared to illumination distance in order to minimize any nonsymmetrical shadow which would result in an error computing part orientation. If these requirements are not satisfied, an intermediate step must be considered. It is expected that future research on the development of high-speed pattern-matching techniques and the establishment of design guidelines for effective part-presentation would decrease the sensitivity of the location and orientation computation to environment effects.

The concept of "engineered landmarks" appears to be an effective solution for applications where the object silhouette is not a practical means to characterize the part and where parts can be designed or modified to include landmarks. Further research is clearly needed to investigate the influence of the shape, size, and application methods of the retroreflective landmarks on the part-presentation accuracy, particularly on part orientation measurement. The only work to date investigated the influence of the landmark diameter on the centroid calculation of a circular landmark, Dickerson et al.¹⁴

CONCLUSIONS

The concept of giving retroreflective material an integral role in sensing for generic part-presentation for robotic part-feeding has been presented. This article illustrates the principle, the implementation technique, and the application examples.

Retroreflective vision sensing for part-presentation uses structured surface reflectance rather than object-dependent adaptive lighting to enhance image contrast. The technique does not rely on knowledge of a detailed object geometry or of the surface reflectance of the object and its background. Retroreflective materials can be used as a background in generic part-feeders or as landmarks on parts. In general, the technique has potential applications where the

orientation of the parts can be inferred from the object silhouette or where parts can be redesigned to include engineered landmarks.

Retroreflective vision sensing requires very low-intensity colocated illumination to create a reliable high-contrast digital image for the determination of the parts' location/orientation. The advantage of low-intensity illumination is contributed by the use of retroreflective materials, the spectral characteristic matching of the imaging sensor, and as well as the spectral filtering of the ambient lighting. The technique only requires collocation of camera and illumination source. It is expected that retroreflective vision sensing would allow relatively simple camera/illumination hardware, short computational time, low packaging cost in part-presentation applications.

The concept of structured surface reflectance using retroreflective vision sensing has established a rational basis for generic part-presentation. Research efforts are currently directed towards the proof-of-concept feasibility in robotic part-feeding applications and the development of an integrated system satisfying both cost and functional requirements. The results have led to several new challenges which include part/package design guidelines for effective part recognition and grasping, and high-speed feature extraction algorithms that are effective in the presence of environmental noise.

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