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Flexible part-feeding system for machine loading and assembly.
Part II. A cost-effective solution

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Abstract

The cost to feed parts to a robot for either machine loading or assembly has been recognized to be excessively expensive. To reduce the cost, the design of a fully integrated vision-guided part-feeding system has been developed and constructed. The integrated vision system, which is designed to combine maximum flexibility and reliability with minimum cost and cycle-time, is a flexible computer-controlled system which takes maximum advantage of retroreflective vision sensing for feeding parts onto machine tools or assembly processes. Since the retroreflective material has a distinct surface reflectance that is not commonly found in nature or man-made objects, it enables reliable digital images of high object-to-background contrast to be obtained without a prior knowledge of object geometry and surface reflectance. As will be demonstrated, these attractive features enable the location and the orientation of the part to be determined with relatively simple, high-speed computation without the need for a detailed reflectance map of the parts to be handled. In this article, the design principle, the functional structure, and the operation procedure of the integrated part-feeding system are presented. The concept feasibility is demonstrated experimentally using a prototype integrated vision system.

1. Introduction

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 need has been addressed as a general industrial vision based on bin-picking problem by several authors. However, variations in surface reflectance coupled with algorithm computational demands often make this approach too expensive, unreliable, and slow. Furthermore, the parts are often in separate, regularly spaced locations in totes, pallets, or kits without maintaining sufficient dimensional accuracy to permit loading or assembly by a totally pre-programmed robot. To maintain sufficient position accuracy in transport would often require excessive packaging costs and results in a lack of flexibility. In these cases, the part location is approximately known, and the problem is to precisely locate known objects.

Perhaps, the two most commonly used approaches are the employment of dedicated part-feeding apparatus such as vibratory feeders, conveyor belts, and the specially designed pallets for each part family. Mechanical feeders have often been blamed for the source of a large percentage of work stoppage and defects. For small volume production, the success of specially design pallets is achieved at the expense of operational cost and flexibility. The high operational cost is accountable for excessive packaging costs for transport, precise alignment of the pallet, and re-engineering for new pallet. Although it has been well recognized in the past decade that vision can add considerably to flexibility to part-feeding, several factors limit the standard machine vision techniques for practical part-feeding. Apart from the high equipment cost, two major problems often associated with the use of standard vision are poor reliability and excessive image processing time, both of which depend on the illumination technique, the complexity of the geometry, the surface reflectance of both the background and the objects to be handled.

This paper presents a cost-effective solution to flexible part-feeding along with the demonstration of proof-of-feasibility. The high degree of flexibility is realized through the creative use of retroreflective vision sensing [1] to eliminate the hardware redesign which, otherwise, is necessary to adapt to product change. As has been shown in Part I of this article, retroreflective vision sensing requires very low intensity collocated illumination to create a reliable high-contrast digital image for the determination of parts' location/orientation. The unique features of retroreflective vision sensing have led to the development of a computer-controlled integrated vision system for presenting parts' location precisely to robots or other types of manipulators for machine loading or assembly processes. As will be demonstrated, the system allows relatively simple camera/illumination hardware, short computational time, low packaging cost in part-presentation applications. Since the use of retroreflective materials does not introduce any new limitation to the two-dimensional part recognition problem. The system allows the use of some simple vision processing and calibration procedures introduced and developed by others.

The remaining paper is organized as follows: Section 2 provides an overview of the part-feeding system approach and the functional organization. The part-presentation algorithm is described in Section 3. Section 4 presents the functional description of the prototype integrated system. Application and cost considerations are discussed in Section 5 and the conclusion is given in Section 6.

2. Overview of part-feeding system organization

A workcell of an automated factory typically consists of a robot, a part-feeder, an end-of-arm tooling section, and the manufacturing process as shown in Fig. 1. The part-presentation system is organized as shown in Fig. 2, where the homogenous coordinate system transformations are defined in Fig. 3. The following is a list of definitions for the various coordinate frames shown in Fig. 3.

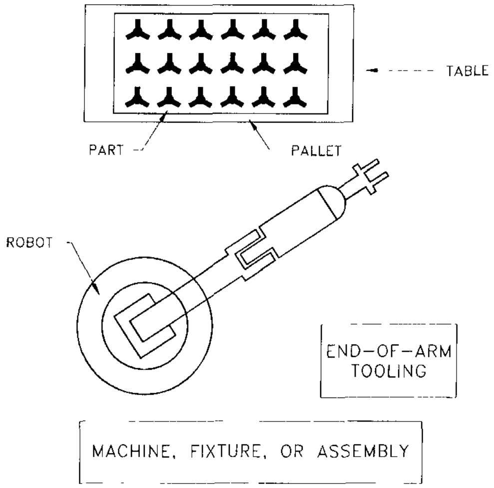


Fig. 1. Schematic of a typical workcell configuration.

r : The robot world coordinate frame is fixed in the robot workstation and serves as a frame of reference in the system kinematics. As the robot arm moves around, the measurements of robot joints enable the robot controller to determine the gripper's location/orientation with respect to the robot world coordinate frame.

g : The gripper coordinate system is fixed on the end-effector-mount of the robot and as the robot moves, it moves with the end-effector-mount.

f : The finger (or hand) coordinate frame is attached centrally between the finger tips. The z-vector lies in the direction that the hand would approach an object and the y-vector is in the direction towards one of the fingertips. As the gripper coordinate frame, the finger coordinate frames moves with the hand.

c : The camera coordinate system is fixed on the camera with the z-axis coincides with the optical axis, and the x, y-axes parallel to the image plane.

b : The board world coordinate frame is an arbitrarily selected but fixed coordinate set on the table on which the pallet is placed.

Coordinate transformations between any two

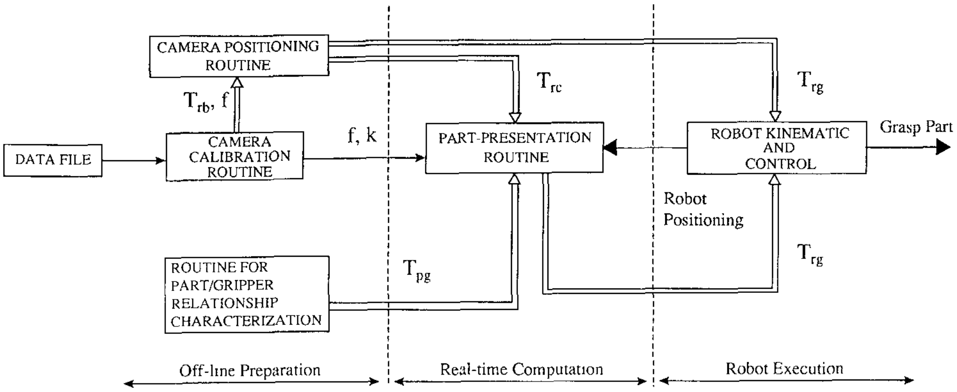


Fig. 2. Part-feeding algorithm

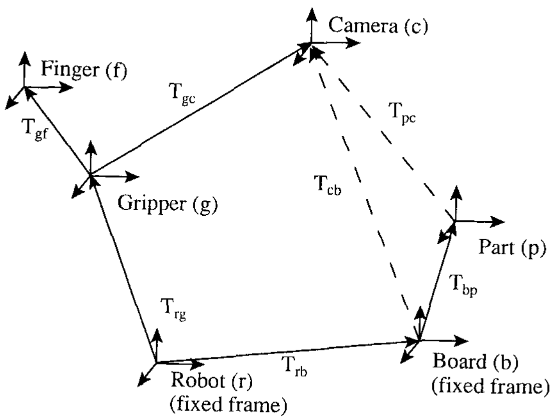


Fig. 3. Kinematic relationship of part-feeding system.

coordinate frames are described by means of 4×4 homogeneous transformations. The notation T_{rg} in Fig. 3 refers to the coordinate transformation from the gripper coordinate frame "g" to the robot coordinate frame "r".

The function of the robot is to serve as the host and thus control all system activities. In the system discussed here the robot is treated as a black box. In other words, the forward and inverse kinematics, trajectory generation, and motion control of the robot are handled by the robot controller. The system is calibrated so that the part location, and the position and orientation of the gripper are presented to the controller with respect to the robot world frame.

Thus, in commanding the robot to pickup a given part, the gripper coordinate frame is determined with respect to the robot world (reference) frame:

$$[T_{rg}] = [T_{rc}][T_{cp}][T_{pg}]$$

As shown in Fig. 2, the robot is driven by (1) sensory information from a retroreflective vision guided part-presenter which determines $[T_{cp}]$, (2) inputs from the off-line calibration which calibrates the focal length f and the lens distortion coefficient k of the camera as well as the camera location $[T_{rc}]$, and (3) data which characterizes the relationship between the part and the gripping configuration $[T_{pg}]$.

The basic principle of the retroreflective vision sensing is to structure the surface reflectance of the pallet or the landmarks so that it is much brighter than objects generally characterized by diffuse or specular surfaces. In practice, a number of non-predictable 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 part design can be modified, brightly illuminated retroreflective landmarks can be intentionally created on objects for location tracking as illustrated in Fig. 4a. Low cost landmarks could be incorporated in design by using retroreflective liquid paints on existing features. Alternatively, generic landmarks can be constructed by applying solid glass beads on reflected surface of standard fastening devices such as screw heads. Solid glass beads (4–200 μm) are available at low cost, ranging from US\$0.15–US\$0.80 per pound (1 pound = 0.4536 kg) depending on the size of the glass bead and the quantity purchased.

If the orientation of the parts can be character-

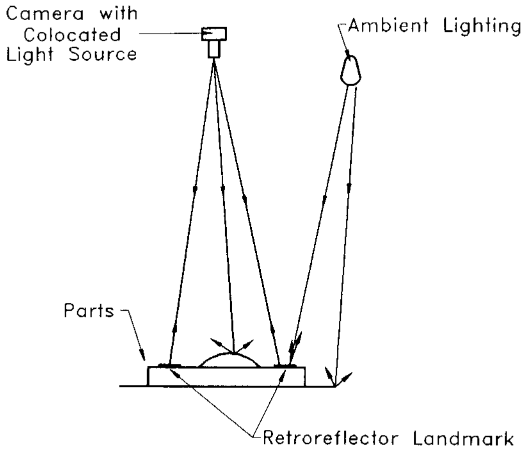


Fig. 4. (a) Engineered object "landmarks". (b) Structured retroreflective background.

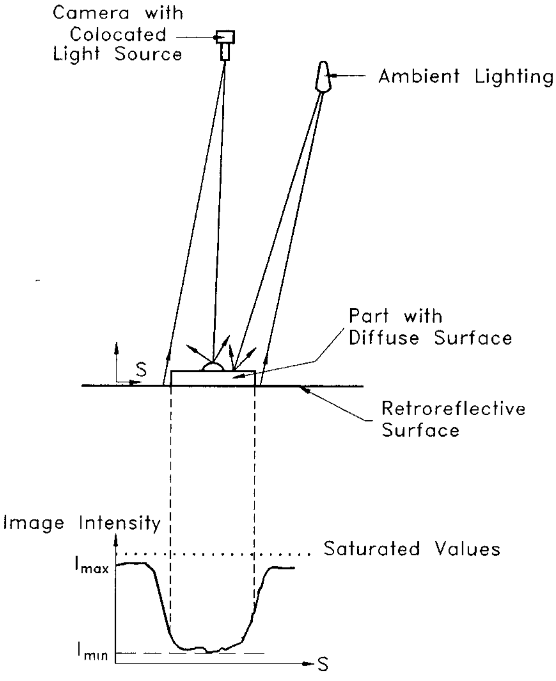


Fig. 4. (b).

ized by the two-dimensional object silhouette, retroreflective materials can be used as a background in generic part-presentation. The principle is illustrated in Fig. 4b. 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, the object appears as a dark silhouette against a reliable bright-field background. In order to eliminate the needs to apply retroreflective materials on each of individual trays, the generic egg-crate-style tray is transparent such that when it is placed on a retroreflective surface, the object will appear as a dark silhouette against a reliable bright-field background.

A typical cycle of the system starts with the arrival of a new pallet with a stack of full part trays via an AGV, conveyor or forklift. The pallet is placed onto one of two or three stands with guide rails to achieve fairly accurate positioning. After the robot has emptied one of the adjacent pallets it will begin unloading the new pallet. To accomplish this, the robot positions the camera high above the nominal center of the pallet and determines both the height and offset from nominal of the top tray. The tray has several landmarks and through triangulation the vision system determines the tray's position. The robot has in memory the location of N regions on the tray and will go to the center of each region independently and determine the offset and orientation of the part. With that information it picks-up the part and performs the loading or assembly operation as required. When all N regions have been emptied, the robot will remove the empty tray and repeat its cycle on the next tray. The pallet has a special pattern to notify the robot that it is empty and the robot will shift over to the next pallet. The only manual intervention required for this cell is that an operator bring in new stacks of parts and remove empty trays and pallets.

3. Part-presentation algorithm

In order that the process can be operated at full capacity, it is necessary that the total cycle-time required by the part-feeding to be less than the process cycle-time. Thus, the part-presentation must be computational efficient. The part-presentation algorithm is developed based on the following assumptions:

a. Parts are placed at a determined height in a regularly spaced egg-crate-style pallet, unoriented but with the right-side-up. This assumption does not pose a serious restriction as it is most often done today. In principle, the separation of parts in egg-crate-style pallet is not a necessary requirement but it reduce the efforts of image segmentation computation for isolating the part to be handled.

b. The orientation of the part can be determined from the object silhouette and/or retroreflective markings. Otherwise, a follow-up step must be considered.
c. The part-gripper relationship is a known priori. For most industrial applications, the description of the parts are usually known and can be precompile off-line.

3.1. System calibration

The camera is mounted along with the gripper on the end-effector mount of the robot. This allows complete freedom in positioning and orienting the camera for viewing. Placing the camera on the last link of a six DOF robot enables the machine vision to view pallet cells individually. The camera is oriented so that its line of sight is perpendicular to the pallet plane and its rectangular field-of-view (FOV) is parallel to the rectangular cell dividers. However, at each position, the 3D position and orientation of the feature measured by the vision system is only relative to the vision sensor. In order to determine the 3D position and orientation of the feature with respect to robot world coordinate, it is necessary to calibrate the relative homogeneous transformation $[T_{gc}]$ between the two coordinate frames, one centered at the camera and the other at the gripper. The purpose of the system calibration is to establish the relationship between the 3D world coordinates as seen by the robot and their corresponding 2D image coordinate as seen by the computer. The calibration algorithm consists of (1) calibrating the intrinsic parameters of the camera f and k, and (2) calibrating the camera-gripper relationship, $[T_{gc}]$, and (3) one-line calibrating the pallet location $[T_{cb}]$. The camera calibration is developed based on the theoretical framework originally established by Tsai and Lenz [2–5].

3.2. Off-line determination of part-gripper relationship

In commanding the robot to execute a part pick-up task, it is necessary to specify the gripper coordinates. For this, the geometric relationship between the part and gripper must be specified. It is desired that the acquisition of the part-gripper relationship be obtained without a need of detailed geometric programming. This would reduce the skill and time needed by the system operator. The gripper-part relationship can be determined by the use of a teaching gripper which has "engineered landmarks" located on the fingers to indicate the desired gripper coordinate frame with respect to a sample part. The approach requires two images, a silhouette of the part itself and a silhouette of the combined part and gripper's "engineered landmarks", both of which are acquired with the sample part maintained in the same location. The characteristic part-gripper relationship is computed from the transformation between the coordinate of the part and that of the desired gripping configuration, which are described with respect to a common reference frame. Alternatively, the image of the part to be taught is displayed, using a cursor, the gripper position is located on the image by the user. The orientation and approach position is then entered by the user via the keyboard.

3.3. On-line part-presentation

The functions of the real-time part-presentation are to acquire and to enhance image, to compute the location and orientation of the digitized image, and to present the computed data to the robot controller.

3.3.1. Image enhancement

Once the vision system has determined the location of the tray, the optimal viewing position for each compartment is computed, taking lighting and part size into consideration. The camera is then positioned above the compartment and an image is acquired and loaded into the video RAM (random access memory). It must then be processed to determine where the part is in the image, provided that the image quality is sufficient.

To insure that high contrast is maintained, software control of the image integration period has been implemented to control the "exposure" time of each image. When a region of an image becomes saturated, the image has been "over exposed" and the integration time is reduced for subsequent images. Also, if the peaks of the bimodal distribution are too close together, the integration time is increased to improve the contrast.

Due to the high contrast images obtained using retro-reflective sensing, relatively simple thresholding can be used to distinguish parts and/or landmarks from the background tray. Thresholding involves converting a grayscale image into binary image to reduce the amount of information that needs to be processes. Feature extraction and image segmentation routines are simplified and execute much faster on binary images. The histogram of a typical high contrast image is a bimodal distribution. A simple algorithm for locating the minimum point between the two peaks is used to automatically determine a threshold for binarization of segmentation routines.

3.3.2. Feature extraction

The use of retroreflective vision sensing which generates reliable high contrast silhouettes effectively minimizes the image segmentation computation. However, in order to eliminate noise caused by electromagnetic interference, dirt on the retroreflective material or CCD, and ignoring the other objects in the field of view, image segmentation is performed before the computation of the part location and orientation. An image segmentation algorithm is written to locate regions of pixels that are connected and to label each region (object) so that it can easily be picked out from the other regions in the image. After segmentation is complete, the center and the orientation of the largest object in the image can be computed.

3.3.3. Communication protocol

To ensure data integrity during communications, DEC's Digital Data Communications Message Protocol (DDCMP) is used for communications with the vision system. DDCMP is an industrial standard communication protocol that is used to communicate with industrial robots. DDCMP ensures a reliable communications link with a minimum amount of overhead. DDCMP precedes all data transmissions with a header block describing the type of message and the length of any message data that follows:

TYPE	COUNT	FLAGS	RESP	NUM	ADDRESS	CRC	DATA...	CRC

The TYPE field determines if the message is a control message or a data message and the COUNT field is the length of any data in the message. The ADDRESS field is the address number of the station the message is being sent to, allowing more than two systems to communicate on the same network. The two CRC field are used for error detection in the header block and the data that follows it. The data following the header block contains information and error messages. In the case of the PUMA, the data is normally ASCII text, where as the data is encoded in the T3 robot.

4. Prototype integrated vision system (IVS)

To demonstrate the concept feasibility, a fully integrated machine vision system which allows a micro-processor (μP) to have direct control of the imaging sensor was built upon the electronic framework of a landmark tracking system (LTS) [6]. The integrated vision system uses a Texas Instruments charge-coupled-device (CCD), directly coupled to an controlled by a Motorola 68000 micro-processor (μP).

The functional description of the electronics is shown in Fig. 5. The system has three functional modules: (1) The single-board computer consists of an μP and its associated EPROM, RAM, and communication interface. (2) A video head which includes the CCD, the high bandwidth signal conditioning amplifier, and the analog-to-digital (A/D) converter. (3) The optical lens and its associated co-located illuminator for retroreflection. The μP allows the direct control of the CCD array scanning and integration time, the intensity of the co-located illumination, and the real-time execution of the on-line part-presentation. The communication between the μP-based computer, the supervisory computer where off-line part-gripper relationships are characterized, and the robot controller is interfaced through the Motorola MC68901.

Since the original LTS was designed for track-

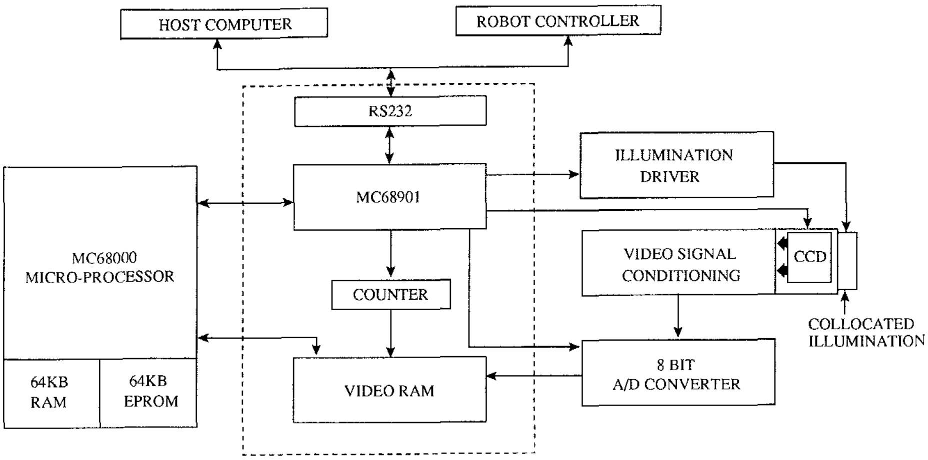


Fig. 5. Schematics of integrated vision system.

ing pre-defined circular landmarks in AGV navigation, several modifications were made on the system electronics for generic part-presentation. The modifications include the increase of communication speed from a baud rate of 2.4K to 38.4K, the addition of an anti-blooming circuitry, and the realization of the direct control of integrating time and illumination intensity. The integrated vision system built with US$250 worth of electronic components is shown in Fig. 6.

The camera hardware was modified to allow the use of standard C-mount lenses since they are best suited for use on camera with small sized array length (diagonal dimension of the CCD photosensitive surface less than 10 mm), relatively inexpensive, and interchangeable. Twelve HP4101 AlGaAs LED lamps (100 mW each) are evenly spaced at a 25.4 mm (1 inch) diameter from the center of the 16 mm C-mount lens. 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. A spectral filter of 650 nm was placed in the light path between the LEDs and the lens.

5. Application considerations

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

5.1. Selection of collocated illumination source

Imaging sensors are characterized by their specific bandwidths or wavelengths of light which maximize the response of the sensor and will provide it an optimum operating environment. It is desired that the photodetector responses only to the light from the illumination source structured for retroreflector but not that of ambient lighting. A typical sensor/illumination system for retroreflective part-feeder may consist of a camera imaging sensor, a spectral filter, and a spectral illuminator.

5.1.1. Responsivity curve of sensor

The relative responses of the two most commonly used camera imaging sensors, namely, Charge-Coupled Device (CCD) [7] and Charge Injection Device (CID) [8], are shown in Fig. 7a. 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 response and has a peak spectral response about 650 nm. The relative response of vidicon camera [9], however, depends significantly on the materials as shown in Fig. 7b. The comparison between three different cameras is given in Table 1.

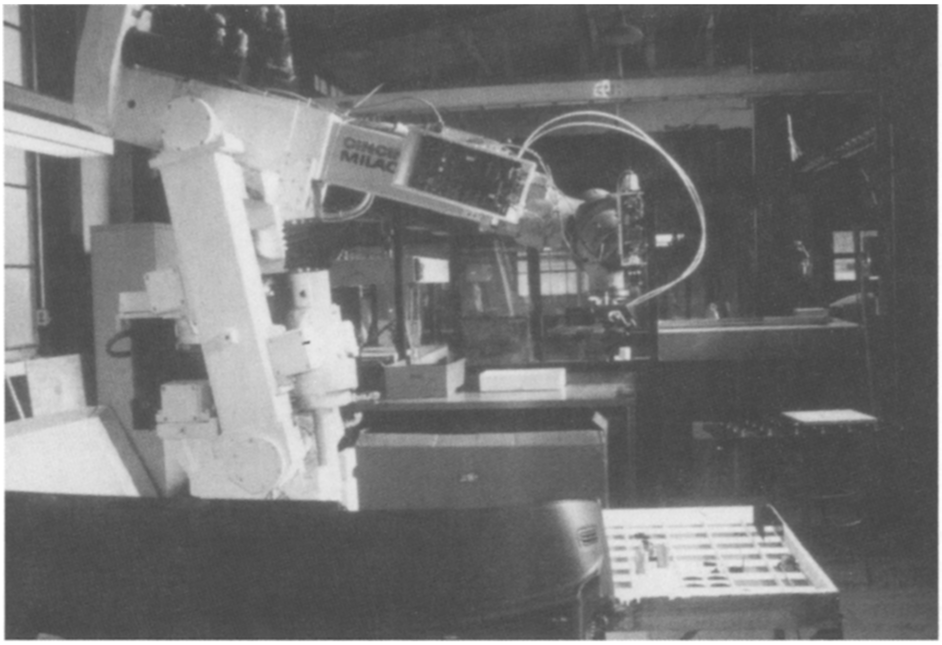


Fig. 6. Prototype integrated vision system. (a) Testbed layout; (b) micro-processor control hardware; (c) digital camera

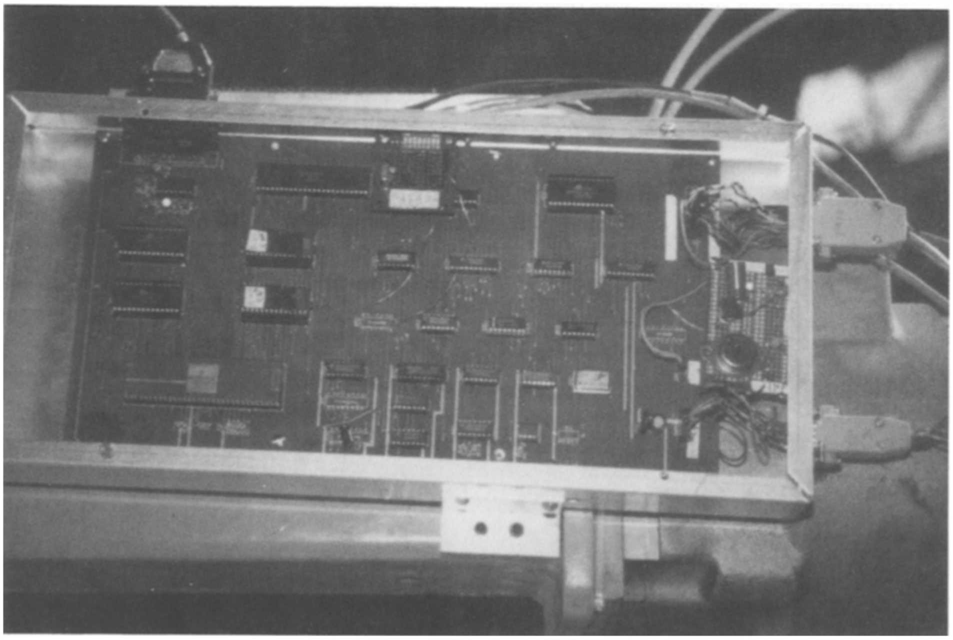


Fig. 6. (b).

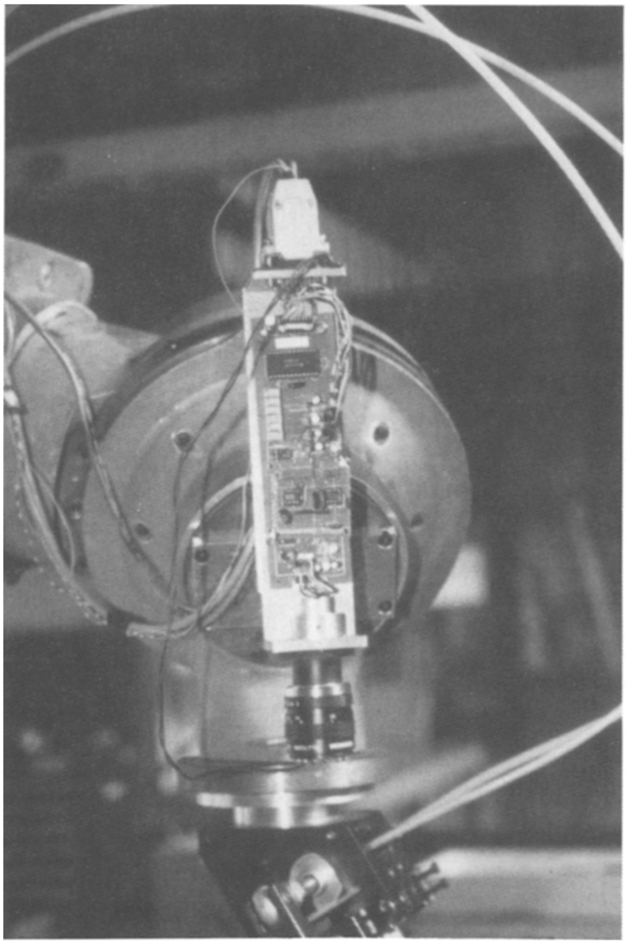


Fig. 6. (c).

5.1.2. *Spectral characteristic of typical ambient lighting*

Depending on the spectral emissions of illumination sources used as general lighting in factory environment, the influences 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. Sun, tungsten lamps, and quartz-halogen type lamps have a wide spectral response.

The spectral characteristics of three different spectral sources, namely laser diodes, LED lamps, and xenon strobes, are of particular interests since the spectral wavelengths of these sources well match the optimal response of the CCD and/or CID detectors. Pulsed GaAlAs Laser diodes [10] emits 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 [11] which is designed to concentrate the luminous flux into a narrow radiation pattern to achieve high intensity have a narrow peak intensity at approximately. The comparison between three different sources is given in Table 2.

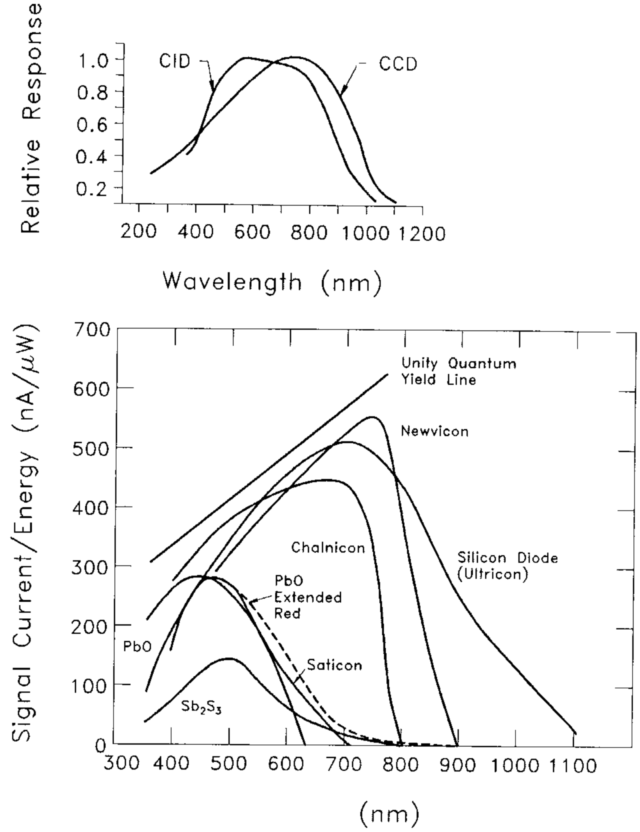


Fig. 7. Spectral characteristics of typical camera imaging sensors. (a) Spectral characteristics of CCD and CID Devices; (b) spectral responses of various photoconductors.

5.2. *Types and properties of retroreflective surface*

The most commonly retroreflective surface is in the form of sheeting due to its reliability and ease of applications. The flexible retroreflective sheeting is made of countless micro cube-corners or spheres enclosed in a weather resistant transparent plastic film. Pigment or dye can be inserted into the film onto the reflecting surface to reflect color. Four typical retroreflective sheeting

TABLE 1

Typical commercial camera

Camera type	Output (frame/sec)	Dimensions and weight	Pixel size	Active elements	Cost US$
Hitachi Vidicon	RS170 (30 F/s)	8.5″×2.9″×4.1″ 1 lb.	not applicable	not applicable	$300
Hitachi CCD	RS170	2.2″×2.1″×3.3″ 1 lb.	not available	570×480	$900
CID 2507[a]	RS170	3.37″×3.0″×3.64″ 1 lb.	23.4 μm×13.8 μm	377×237	$2250
CID 2220[a]	RS170 compatible 60 F/s	3.37″×3.0″×3.64″ 1.25 lb.	square pixel	256×256	$2200
EG&G CCD[a]	25–105 F/s[b]	1.7″×2.5″×2.5″ 0.75 lb.	square pixel	256×256	$2200

[a] Required an addition Video data Formator ($1500/-).

[b] With rapid scanning for selective data extraction.

TABLE 2

Comparison between three spectral light sources

Source	Wavelength (nm)	Unit cost US$	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/sec)	25 W (500 V nominal)

are described as follows: (1) cube-corner retroreflective sheeting, (2) exposed glass bead, (3) enclosed glass beads, and (4) encapsulated glass beads.

The cube-corner retroreflective sheeting, as illustrated in Fig. 8a, is typically manufactured with an air cushion behind the cubes. The cube-corner retroreflective sheeting is characterized by its high coefficient of retroreflection at low entrance angle which means it appears bright at long distances.

In exposed lens sheeting, the front half of the glass beads are exposed to the outside air if the device is not too far laterally removed from the light source as shown in Fig. 8b. Glass beads work best when exposed to the air. Water, oil, or dirt covering the beads will greatly reduce the reflectivity of the beads. Exposed lens sheeting can also be made from retroreflective paints.

Enclosed lens sheeting is made by imbedding glass beads in a layer of transparent plastic of appropriate color as illustrated in Fig. 8c. A metallic reflection shield is provided behind the plastic, plus a layer of adhesive an a protective liner that is removed prior to applications. The plastic covering enables the sheeting to be equally bright under dry and wet conditions.

The construction schematic of the encapsulated lens sheeting is shown in Fig. 8d. The glass beads are protected by a transparent material that is supported slightly above the beads walls leaving an air filled compartment. The back of the beads are covered with a reflective surface. The resulting air space in front of the beads makes it more reflective, and hence, is known as high performance sheeting.

Typical distribution of retroreflected light from several different types of materials as functions of observation and entrance angles are compared in Figs. 9 and 10, where the coefficients of retro-

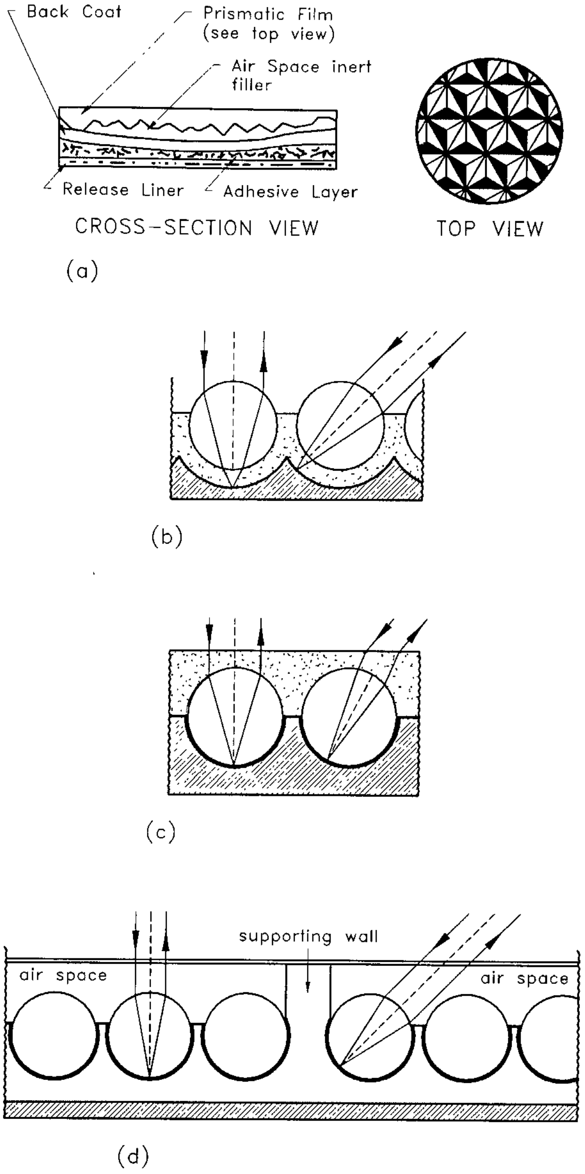


Fig. 8. Examples of typical retroreflective sheeting. (a) cube-corner retroreflective sheeting; (b) exposed glass beads; (c) enclosed glass beads; (d) encapsulated glass beads.

reflection have been normalized to their respective peak values. The absolute peak values are given in cd lux^{-1} m^{-2} in the parentheses. The effective life and unit cost are given in Table 3.

5.3. Illustrative example

Machine components are often fabricated from raw materials which may be pre-cast, pre-drawn, or pre-formed 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. Fig. 9a shows two typical machine components to be presented for machine loading. The object on the left is a typical component prior 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 Fig. 9b. 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.

Alternatively, common re-usable pallets are used to house the components for several different machine processes. The pallet could be a generic rectangular container with a retroreflective surface on which an egg-crate-style transparent tray can be placed. This pallet design offers several advantages: (1) It reduces the application of retroreflective sheetings on individual trays to a minimum. (2) It allows flexibility to accommodate different part sizes without the needs to re-apply retroreflective materials for new part change-over. (3) It allows different tray configurations to be interchangeable for use with the retroreflective container. Fig. 9c displays the image of the machine component as shown in Fig. 9a. Due to highly intensive retroreflectance and the ability to direct control of the integration time, the simple optic allows low-power spectral source to be used to faithfully produce a high object-to-background image for location and orientation computation.

5.4. Computation speed

The computation speed of the IVS has been estimated using the IVS. Since the computation of the centroid and orientation of image was per-

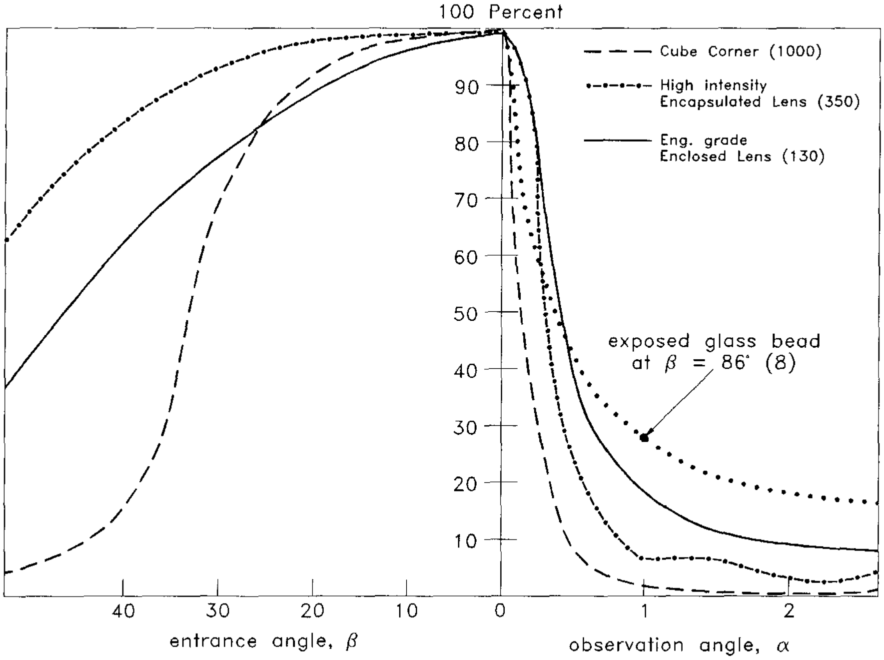


Fig. 9. Comparison between different types of retroreflective sheeting.

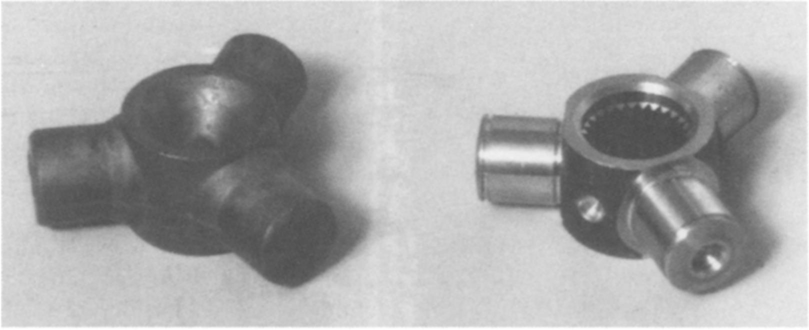


Fig. 10. (a) Typical machine components; (b) conventional digital images of machine components; (c) digital image of machine components taken using IVS with retroreflective background.

TABLE 3

Cost of performance life of retroreflective materials

Type	Cost US$	Effective performance life
Retroreflective liquid-exposed glass bead	approximately $0.30 per square foot	4– 5 years
Engineering grade – enclosed glass bead sheeting	$0.60–$1.00 per square foot	5– 7 years
Super-engineering – enclosed-glass-bead sheeting	$1.60–$1.90 per square foot	7–10 years
Encapsulated sheeting – glass bead	approximately $3.00 per square foot	10 years
Encapsulated – prismatic	approximately $3.00 per square foot	10 years

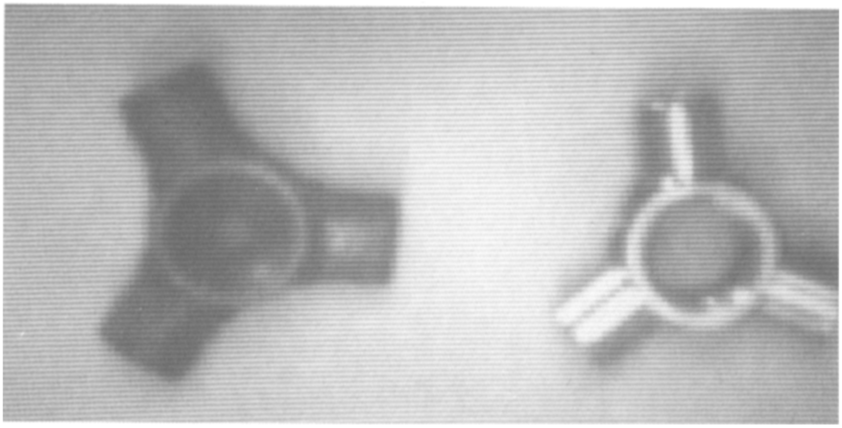
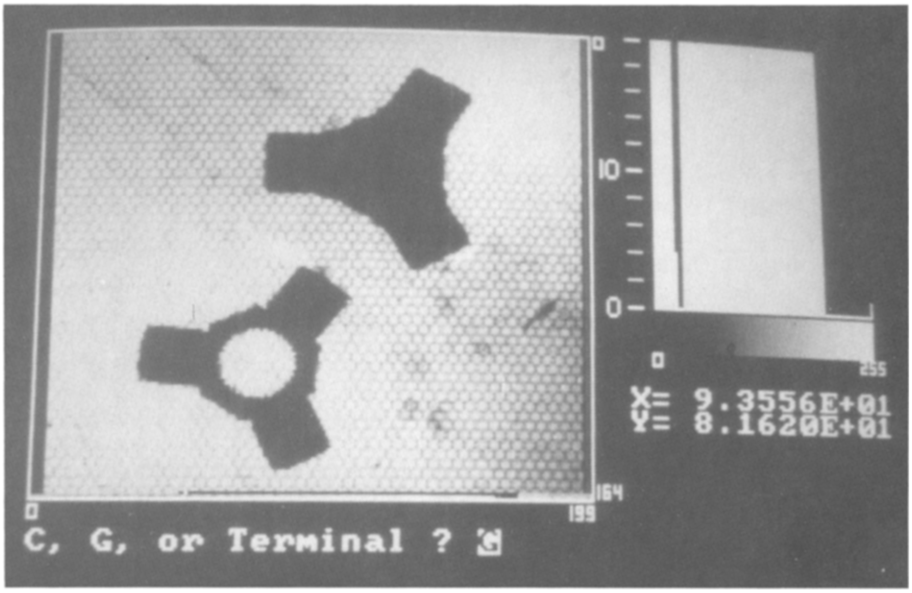


Fig. 10 (b).



```
X= 9.3556E+01
Y= 8.1620E+01
C, G, or Terminal ?
```

Fig. 10 (c).

formed by the on-board microprocessor written in assembly language [6], the image transfer from the IVS to the host computer in real-time application is not necessary. The IVS communicates with an IBM PC/AT which is used as a host at a baud rate of 9600 through RS 323 communication serially. The baud rate of 9600 was chosen since it is commonly used in industrial robots today. The IVS digitizes the video image (165 rows by 195 columns) and stored in the video RAM a rate of 8 ms/frame (125 frames/second). The total time required for processing an image using IVS depends primarily on the integration time of illumination, the communication time, and the computation time of part location. A typical example of the time distribution for processing an image using the landmark locating function in the IVS is given in Table 4, where the computation is based on the window size 132×169 (approximately 68% of the full frame) containing a single landmark of 240 pixels. Clearly, the integrated vision system offers significant advantages over the breadboard configuration [12] in terms of processing speed and cost.

TABLE 4

Image processing time distribution

Process	Time
RS232 Communication between host and IVS	9.4 ms
Illumination time	21.5 ms
Frame transfer from CCD to Video RAM	8.25 ms
Computation time	38 ms
Data transfer from IVS to host computer	22 ms
Total	99.15 ms

6. Conclusions

This paper has presented a cost-effective solution to vision-guided part-feeding. The investigation has led to the development of a computer-controlled integrated part-feeding system as essential peripheral equipment for flexible manufacturing automation.

The concept of giving retroreflective materials an integral role in vision sensing for generic part-presentation has been proven to have significant potentials in improving the vision reliability, reducing the computational load/time, and lowering the cost in implementation for part-feeding. Research effort is being directed towards the development of high-speed computational algorithms, analytical models, and design tools for effective implementation of the vision-guided part-presentation on shop-floor. It is expected that future research would stimulate other engineering challenges including the development o- f low-cost application of retroreflective materials for manufacturing automation applications.

It is important to point out that the manner in which parts are fed to robots in a FMS depends on the nature of the manufacturing processes, the product design, and the material handling system as a whole. The research in generic part-presentation system is expected to provide insights to the overall manufacturing system modeling and simulation, guidelines for part-presentation equipment standardization, and would aid establishing guidelines for part-design and part-packaging for high-performance feeding.

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