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Effect of light source on the sorting performance of a vision-based robot system

Johnny T. Li
University of Northern Iowa

EFFECT OF LIGHT SOURCE ON THE SORTING

PERFORMANCE OF A VISION-BASED ROBOT SYSTEM

A Dissertation

Submitted

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Industrial Technology

Approved:

Dr. Ahmed ElSawy, Advisor

Dr. John Fecik, Co-Advisor

Dr. Guru Subramanyam, Committee Member

Dr. Carmen Montecinos, Committee Member

Dr. Eugene V. Wallingford, Committee Member

Johnny T. Li

University of Northern Iowa

May 1996

UMI Number: 9633450

UMI
300 North Zeeb Road
Ann Arbor, MI 48103

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Dr. John W. Somervill, Dean of the Graduate College

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ABSTRACT

Industries look toward computer vision as a means to automate materials handling. To make this choice more appealing, useful and feasible vision applications must be explored. However, illuminance variation in the factory environment can undermine the capability and applicability of vision-based control systems. The purposes of this study were (a) to design and develop a vision-based robot material sorting system, (b) to determine the optimal system settings for this system under fluorescent and incandescent lighting for two different color parts on a moving conveyor, and (c) to determine the sorting performance of this system under each light source.

The main components of this experimental system consisted of: (a) a SCORBOT ER-V plus (ESHED ROBOTEC) robot system with a slide base and a speed controlled conveyor, (b) a ROBOTVISIONplus vision system, (c) an incandescent lamp light intensity controller, and (d) two PCs. By integrating these components, color sorting applications were developed.

This study was limited to the sorting of two parts with different colors and similar geometry from a moving conveyor. The system performance (sorting) data were collected on the developed application under fluorescent and incandescent light sources with a conveyor speed of 50 mm/s at various illuminations.

This study explored two sorting methods. Method A used the difference in object descriptors to separate the dominos. Method A worked in a limited range of illuminance and identification tolerance for both light sources. Method B used the difference in the observed "saturation" response of the charge coupled device camera to

difference in the observed “saturation” response of the charge coupled device camera to separate the dominos. The “saturation” response region described the interval of illuminance where changes in illuminance did not produce a corresponding change in objects’ measured grayvalue. Method B worked in a wide range of illumination with no stipulation on identification tolerances for both light sources.

Unexpectedly, the light sources in the laboratory setting exhibited a large amount of illuminance variation, and these variations caused applications developed using Method A to perform erratically for both light sources. However, Method B sorted reliably over a wide illuminance range: 150 to 1500 lux for incandescent and 214 to 760 lux for fluorescent.

CHAPTER I

INTRODUCTION

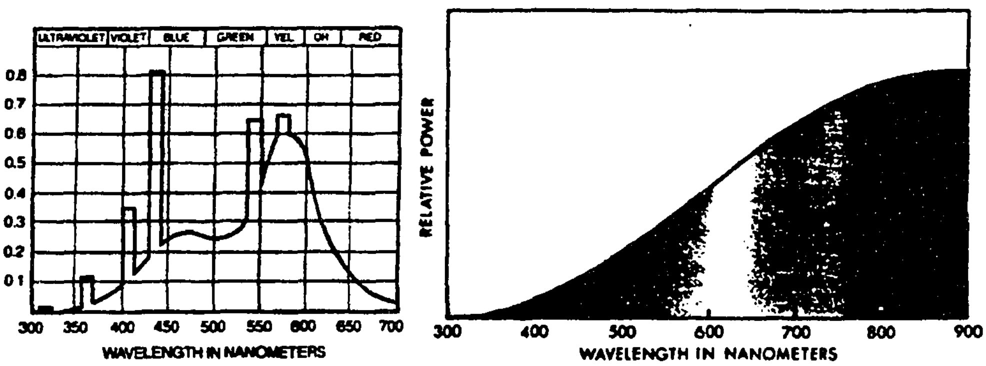
In this research work, the main concern was the development of vision-based robot sorting applications. Development of vision-based applications addressed the industry's need to automate monotonous, routine, and labor intensive operations. These applications were developed based on the integration of a vision-based robot system with two computers. One computer hosted the vision software, and the other performed on-line control and monitoring of illumination and sorting performance.

Computer vision-based robot systems have played a growing role in the automation of material handling (Babb, 1995). According to the Automate Imaging Association, sales of machine vision systems by North American companies had reached $888 million in 1994 and were projected to reach $1.5 billion by 1999. The accuracy of this projection will depend on the ability of the vision system providers to develop useful applications and to solve "real world" problems.

Illuminance variation has identified as one such problem. Lee (1994) addressed this problem in detail:

> Illumination and its measurements are, perhaps, among the least understood technologies. Discussion and communication of desired operating parameters of optics are complicated by a plethora of nomenclatures for seemingly similar units of measurements. Furthermore, system specifications for illumination are often vague and left to the final user. As a result, illumination deficiencies must often be compensated for with expensive digital hardware/software. When illumination deficiencies become apparent, it is then that critical light parameters such as luminous intensity, illumination uniformity, spectral output, and image spectral irradiance become an unwelcome part of our vocabulary. Direct symptoms of an unfit light source are not only long exposure times, but can also include inaccurate image characteristics due to nonuniform illumination. (p. 421)

Stonecipher (1989) identified fluorescent and incandescent lamps as the two most common light sources. Fluorescent lamps have provided the majority of shopfloor lighting; thus for many vision-based material handling systems, they have provided the illumination by default. However the spectral distribution of fluorescent lighting contains regions of sharply varying power levels (see Figure 1); this causes objects that reflect light wavelength in the higher power ranges to reflect more light than objects that reflect light wavelength in the lower power ranges. Incandescent light sources provide more predictable spectral distributions (see Figure 1). This enables a more accurate prediction of the reflected light spectrum. Therefore, developers should consider this alternative light source in vision applications.



(a): F40/CW fluorescent lamp (b): Incandescent lamp

Figure 1. Light sources' relative power spectrum distribution. (a) F40/CW fluorescent lamp (DiLouie, 1994. p. 89). (b): Incandescent lamp. (Kaufman & Christensen, 1972, p. 8-20)

The main components of the automated material handling system in this study consisted of a vision system, a robot system, and two light sources (see Figure 2). The vision system scanned the conveyor to identify objects moving on it and provided the

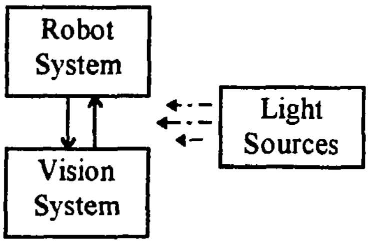


Figure 2. Block diagram of main components in a material handling system.

coordinates necessary for the robot to pick up the object. The robot loaded the conveyor with parts from a gravity feeder and unloaded the identified parts from the conveyor into other gravity feeders. The key ingredient of this automated system was the vision feedback. By performing identifying and controlling operations in real-time, the vision system enabled on-the-fly material handling operations of multiple parts. Because there was a difference in the power distribution spectrum of the fluorescent and the incandescent, the type of light source used should depend on the reflective properties of the parts involved.

Background

Manufacturers have been able to purchase off-the-shelf machine vision systems for the implementation of robot-vision material handling operations. Some of these integrated robot-vision systems could identify and sort objects on-the-fly from a moving conveyor. This ability increased the system's throughput, but also placed additional demands on the system.

Many variables affect the vision-based material handling operation. The following were some of those variables pertaining to the proposed system:

1. Lighting
2. Reflective properties of the objects
3. Response spectrum of the camera
4. Reflective properties of the conveyor belt
5. Speed of the conveyor
6. Speed of the frame grabber
7. Resolution of the camera
8. Image filters
9. Vision identification algorithms
10. Vision identification tolerance
11. Accuracy and repeatability of the robot
12. Synchronization of vision system, robot, and conveyor
13. Computer processing speed

Figure 3 shows the diagram of the developed material handling system with the location and the range of variables affecting the system performance.

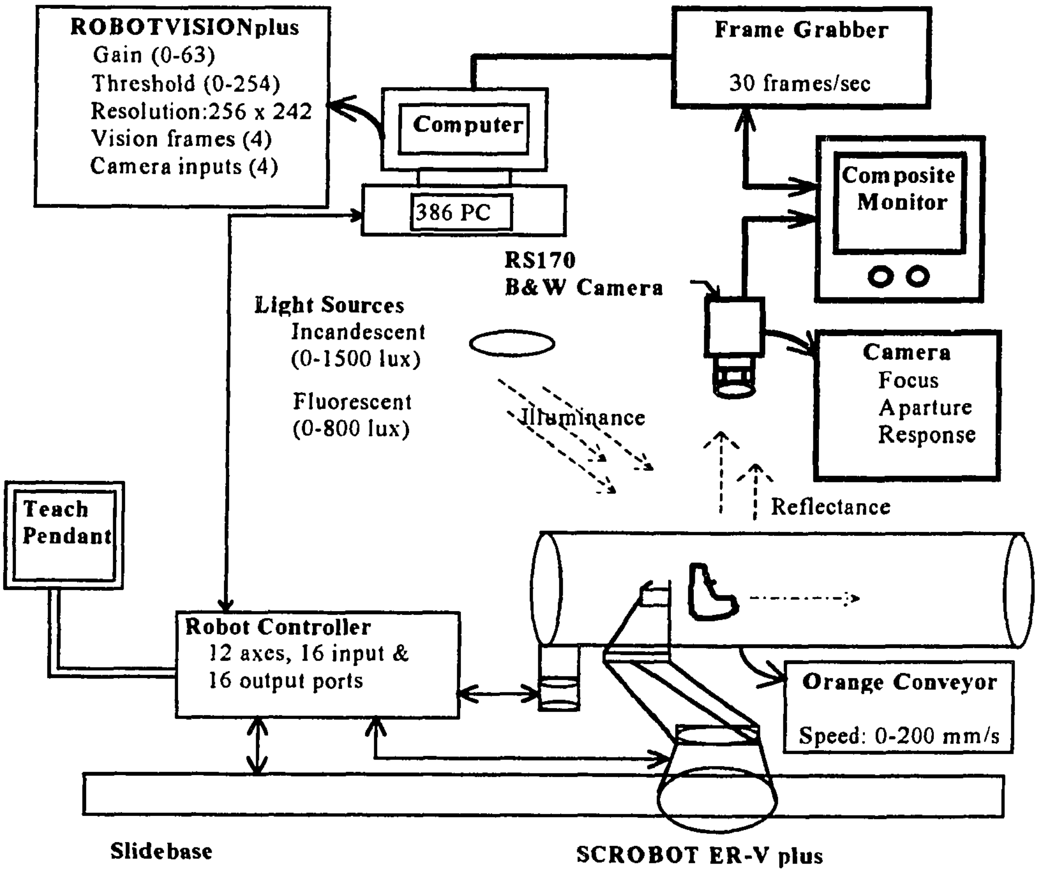


Figure 3. Diagram of the material handling system displaying the location and the range of system settings affecting the system performance.

Lighting was identified as one of the more influential variables, and, because the targeted object was moving, the effects of lighting were even more uncertain. Poor lighting diminished the quality of the initial image and affected every subsequent vision operation based on that image. According to Haim Schleifer, president of Eshed Robotec in Princeton, "Lighting is very important in machine vision applications." Charette, Park, Williams, Benhabib, and Smith (1988) indicated that lighting is critical to the printed circuit board (PCB) flaw detection process. Lee (1994) also identified lighting as an influential factor in vision systems. Further more, lighting influenced the settings of other vision system variables. Variables that depend on lighting consisted of the followings: camera aperture, gain, and threshold. The light aperture of the camera controlled the amount of light entering the camera. The gain setting controlled the amount of amplification. The threshold setting defined the value through which the vision system determined whether a pixel was white or black.

The effects of lighting combined with the effects of the reflective properties of the object could cause a difference in the image obtained by the camera. Different color objects reflected dissimilar light patterns onto the charge coupled device (CCD) camera. The reflected spectrum also depended on the spectral distribution of the light sources. Because the CCD camera absorbed photons in the 400-1100 nm range (see Figure 4), it can only detect reflected light with wavelengths in that range. A white object reflected all light wavelengths in the visible spectrum in nearly equal proportion. A red object reflected more of the light wavelengths in the 700nm-800nm range and absorbed more light in other wavelengths. Because the fluorescent and the incandescent light sources

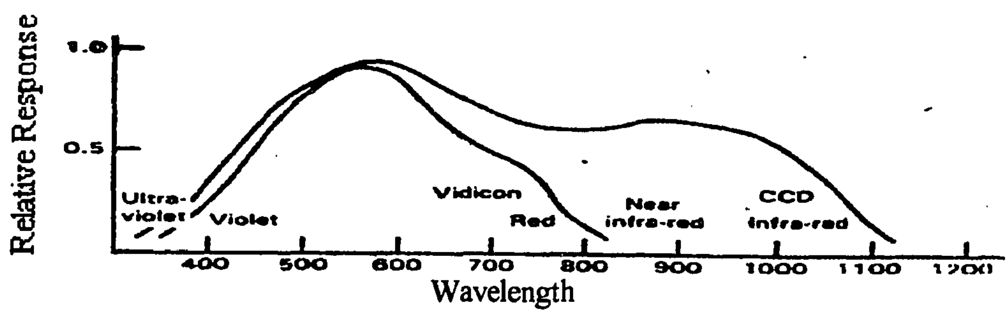


Figure 4. Spectral sensitivity of the vidicon and CCD cameras (Vernon, 1991, p. 25).

produced different relative power spectrums, using different light sources would change the image acquired by the vision system under otherwise similar settings.

The conveyor belt was the background for material handling applications developed through this study. If the reflective property of the conveyor belt was similar to the targeted object, then the vision system could not separate the object from the belt. Also, if the belt surface contained areas of varying reflectance due to uneven surface texture, errors in identification might occur.

The speed of the conveyor had an effect on system performance, because a moving object could distort the image scanned by the vision system. A CCD camera captured an image by measuring the discharged voltage due to photon absorption. A moving object incurred a displacement of reflected light (photons) on the CCD. In view of this, it was reasonable to conclude that higher speed would produce higher image distortion.

The speed of the frame grabber should be fast enough to capture the image from the moving conveyor in real-time. If the speed of the frame grabber was slower than the processing capability of the computer, then it limited the speed of the vision operation. Also, if the frame grabber speed increased, then the distortion caused by the moving conveyor would decrease, because the displacement was less. Furthermore, the speed of the frame grabber influenced the maximum speed of the conveyor, because the duration of the object located in the FOV was inversely related to the speed of the conveyor.

Camera resolution described the number of pixels available to the vision system. Higher resolution would require higher frame grabber speed. Camera resolution also influenced the quality of the acquired image. A higher resolution provided more detailed images, thus more accuracy.

Image filters changed images in pre-defined ways. An image filter could make complex images simpler at the expense of reducing image resolution. The type of filters applied to the image could cause a large change in processing time, accuracy, and usefulness of the system. Using appropriate filters could reduce the variations caused by an ustable illumination source.

Vision identification algorithms determined the identity of the object by searching through the object database for matching object parameter descriptions based on pre-defined sequences. Increasing the number of object parameters used in the identification procedure reduced the chances for false identifications (Type I error) at the cost of increasing the process time and false rejections (Type II error). If a domino was being identified using object descriptors (surface area and perimeter length) as identification parameters, then the system's normal variation would affect both parameters, thus increasing the possibility of rejecting good parts. However, comparing both parameters increased the chances for correct identification. Reducing the number of parameters increased the processing speed and decreased the false rejection rate at the cost of more identification errors.

Tolerance settings of the parameters used in the vision identification algorithms determined whether a match had occurred. Identification algorithms specified search procedures and parameters compared, while tolerances specified the level of matches. If tolerance was set at 10%, then a match occurred when the measured parameter fell within the database parameter ±10%. Higher tolerances reduced the chance for false identification (Type I error) at the cost of increasing false rejection (Type II error). Lower tolerances did the opposite.

Performing a "pick and place" operation from a moving conveyor required a robot system with high accuracy and repeatability. Without accuracy, the robot could not move to the location indicated by the vision system. Without repeatability, the robot could not reliably execute the task specified.

The vision-based robot material handling system needed to be synchronized. Errors in the synchronization process could have a detrimental effect on the material handling system. Correct synchronization enabled the vision system to locate the object on the moving conveyor and to direct the robot to pick up the object.

Lastly, the processing speed of the host computer played a role in all areas of operation. Insufficient processing speed reduced overall performance. Extremely high processing speed would not speed up the overall operation, because the bottleneck was at the mechanical end of the vision-based robot sorting system. However, without adequate computational power, only simply vision operations were possible.

Statement of the Problem

The implementation of a vision-based robot material handling system in an industrial setting was difficult, because of illumination variations. Using the wrong type of light source could limit the number of different colors that could be handled. Because different light sources produced different spectral distributions, arbitrarily using the default lighting may not be the best course of action. Furthermore, the sorting of parts from a moving conveyor presented an additional level of difficulty. This added level of difficulity made light source selection even more important.

A common problem with the illumination quality of the light sources was the fluctuation of the luminous flux due to the AC power grid. The 60 HZ AC power introduced a "flicker" effect to the illumination. Although unnoticed by human beings, the "flicker" might affect the quality of the image. The main AC power grid also exhibited voltage fluctuation in different load conditions. This was especially important in the "factory environment", where heavy loading can cause a large voltage swing in seconds.

Each light source also had their problems. In addition to their uneven spectral distribution, fluorescent lamps require a period of "warm-up time". They were also very temperature sensitive, so varying temperature caused varying illuminance. One of the major problems with using incandescent lamps was the generation of infrared radiation (IR). Human beings could not see them, but CCD cameras were particularly sensitive to

IR. Due to IR's low energy level, their reflectance often registered as a part of the background noise.

To perform "pick and place" operations from a moving conveyor using a vision-based robot system placed even more demands on the imaging sub-system. The problems of light source selection also depended on the vision system's settings and capabilities. These variables in the ROBOTVISON plus were camera aperture, gain, threshold, conveyor speed, camera positioning, robot-vision synchronization, and object orientation. Furthermore, variables affecting the system performance might contain other sub-variables that were not well understood and thus impossible to measure. The problem of this study was to examine the sorting of different color parts from a moving conveyor.

Purpose of the Study

There existed a need to expand and to examine the potential applications of automated vision-based material handling system. The purposes of this study were to: (a) design, integrate, and develop a vision-based robotic material handling system, (b) determine the optimal system settings for this system under fluorescent and incandescent lighting for sorting two different color parts from a moving conveyor, (c) compare the effects of the light sources on the sorting of objects from a moving conveyor, and (d) determine the performance level of the material handling system.

Significance of the Study

Using vision-based robot material handling could automate the identification and "pick and place" of parts from a moving conveyor. This was especially important in flexible manufacturing, where manufacturing occurred in small lots. Productivity was directly related to speed in manufacturing. If the vision-based system needed to stop the conveyor for material handling operations, valuable time was lost. The continual advancement of computer vision technology had enabled PC-based 2-D vision systems to perform on-the-fly material handling. This increased speed, throughput, and productivity. However, this also increased the cost, demand, and complexity of material handling systems.

Previous investigations in the areas of computer vision, machine vision, image processing, and material handling did not focus on the effect of light source on vision-based material handling. Rahmati (1993) studied the intensity-invariant of object recognition and morphology. Chaudhury (1994) obtained motion estimation from sequences of intensity images. Taylor (1993) used vision feedback to perform on-line process control. Preising (1991) performed on-line calibration of robots using vision feedback. While these studies examined a wide range of topics, they did not examine the effect of the light source on vision-based material handling applications.

Fluorescent lamps were often the default light source used in vision application. It was the most common lighting for the factory floor, because it provids lighting that approximates daylight and are efficient. In addition, Vernon (1991) recommended using fluorescent lighting in machine vision applications.

Although incandescent lamps were not as efficient in producing visible light as fluorescent lamps, their illuminations provided a more uniform relative power spectrum than fluorescent lighting. If the IR generated noise did not present a problem, then incandescent lamps might improve the system's ability to sort colors.

Research Questions

Considering the problems and the purposes of this study, the following research questions were developed. They were:

1. How does one select the gain and threshold values under fluorescent lighting for sorting applications at a particular illumination (540 lux)?

2. How does one select the gain and threshold values under incandescent lighting for sorting applications at a particular illumination (540 lux)?

3. What is the success percentage of robot "pick and place" operation at the gain and threshold settings identified by question 1 for fluorescent lighting?

4. What is the success percentage of robot "pick and place" operation at the settings identified by question 2 for incandescent lighting?

5. Over what illuminance range can the developed system successfully sort the dominos under fluorescent lighting?

6. Over what illuminance range can the developed system successfully sort the dominos under incandescent lighting?

Assumptions

The assumptions made in conducting this research were:

1. The degradation of the light intensity output for the light sources used had no significant effect on the results of this study.

2. The illuminance in the factory environment varies.

Delimitations

The delimitations made in conducting this research were that this study only examined the following:

1. Effects of fluorescent (F40/CW) and incandescent light sources (GE 75 Watt SoftWhite bulbs).

2. Effects of two different color dominos with the same geometry.

3. Effects of one conveyor speed (50 mm/sec).

4. Effects on the ability of the ROBOTVISIONplus and the SCROBOT ER-V plus system to sort and to pick up two different color parts from the Eshed Robotic's Orange Conveyer.

Definitions

1. Camera resolution: The total number of pixels in an image frame. For a 2D camera, the resolution is usually represented as an X by Y matrix.

2. Color rendering: The ability of a light source to show the color of objects as compared with a reference incandescent lamp.

3. Color rendering index (CRI): Describes a lamp's color rendering ability. A reference incandescent lamp has a CRI of 100, while a F40/CW has a CRI of around 65.

4. Conveyor: A servo motor driven device with a belt through which materials move from one location to another.

5. Feedback: The signal generated from a sensor or a set of sensors to provide a system the data needed to adjust to changing conditions.

6. Field of view (FOV): A cone shaped space that extends from the camera lens to the viewing area in a 2-D vision system.

7. Filter: A pre-defined pattern or formula imposed on an image to achieve a change.

8. Foot-candle: A measurement of illuminance (units: lumens per square foot).

9. Frame grabber: An instrument used to digitize the analog input from the CCD camera in a format compatible to the host vision system.

10. Grayscale: Shades of black and white pixels that decompose in to different intensity levels (i.e., 256, 512).

11. Grayvalue: Represents the specific values within a particular grayscale level.

12. Gripper: The mechanical end of a robot.

13. Incandescent light source: A hot body material radiating electromagnetic energy in a continuous light spectrum.

14. Illuminance: The amount of light measured in a particular area. Illuminance can be measured in foot-candles or lux.

15. Illumination: The illuminance at a specific location and time.

16. Image processing: The processing of a image gathered by the computer to change the image format.

17. Integrated circuits (IC): The integration of various semiconductor devices on a silicon wafer(s) into a single component.

18. Irradiance: The amount of electromagnetic radiation falling on a surface.

19. Light: A type of radiant energy that can be visually detected. It travels in waves and has both frequency and length. It only occupies a small range of the electromagnetic spectrum.

20. Loading: The moving of objects into a particular location for further processing.

21. Luminous flux: The light output produced by a lamp.

22. Luminance: The amount of light reflected by a surface.

23. Lux: A measure of illuminance (units: lumens per square meter).

24. On-the-fly: Material handling operations that unload objects form a moving conveyor.

25. Off-the-shelf: Standardized parts or systems that can be purchased from existing vendors.

26. Pick up: The robot operation through which the robot moves to the location of the object and grips it with the Gripper.

27. Radiance: The electromagnetic radiant energy emitted into a unit solid angle.

28. Reflective properties: Properties that describe the amount and the spectral distribution that are bounced off an object.

29. Robot accuracy: The ability of the robot to move to a location indicated.

30. Robot repeatability: The ability of the robot to move to a previously trained location at different times.

31. Robot: A mechanical displacement device that is controlled by a computer.

32. Robot vision: A robot function that utilizes the feedback from a vision system to perform assigned tasks.

33. Synchronization: The matching of positions in a FOV of the vision system to the coordinates of the robot and the conveyor.

Summary

There was a need for automated material handling. Vision-based robot systems were capable of satisfying this need. One of the important problems in vision-based systems was the selection of lighting for vision applications. In a factory environment, illumination would be hard to control. This study addressed the need and the problem by developing a material handling system to automatically sort dominos with two different colors and examined the effects of incandescent and fluorescent lamps.

CHAPTER II

REVIEW OF LITERATURE

Background

Various authors described a variety of industrial applications of computer vision in the industry (see Table 1). According to Babb (1995), machine vision was " . . . moving out of a high-tech niche into new applications right in the heart of traditional manufacturing . . . " and "Machine vision has become a core automation technology at some of the largest manufacturers in North America" (p. 79).

The marriage between robot and vision produced an offspring that could react and adopt to the changing environment of the factory. This came just in time to meet the demands and challenges of the global economy. Although vision and robot systems had developed and expanded both in capabilities and applicability, basic questions concerning the effects of illumination remained unanswered.

Table 1

A Collection of 2D and 3D Machine Vision Applications

2-D	3-D
Surface mount placement	Solder joints 3-D inspection
Punch dies inspection	Laser assisted metrology
Automated welding	3-D object recognition
Wafer identification	Automatic alignment
Optical character recognition	3-D surface inspection using CAD data
Visual gesture recognition	

Note. The machine vision applications in this table were assembled from the following references: Cheraghi, Lehtihet, & Egbelu, 1995; Cox, 1986; Davis & Shah, 1994; Kovacevic, Zhang, & Ruan, 1995; Products, 1995; Quinlan, 1995.

Machine Vision, Computer Vision

According to Li (1990) the meaning of machine vision (MV) was synonymous with computer vision. Computer vision was defined as an interdisciplinary field of study that involved vision, image processing and artificial intelligence (AI). For industrial machine vision systems, vision applications were primarily limited to 2 dimensional (2D) images (Vernon, 1991). This contrasted sharply with 3 dimensional (3D) image understanding vision systems that focused on the understanding and the meaning of a scene. Because of this distinction between research and application, the relationships of image processing and artificial intelligence to MV were not clearly defined.

2D and 3D

Common vision systems processed either two dimensions (2D) or three dimensions (3D) images. A basic 2D image sensor consisted of either a camera which captured 2D images or line scanners which scanned an image formed by an object moving at a fixed speed. Vernon (1991) reported that 2D imaging was the most common form of machine vision used in the industry. There were 3 common methods of achieving 3D imaging. Structure lighting in conjunction with image analysis provided depth data by examining the different shades cast by the illumination. Stereo vision achieved 3D by placing two cameras at an angle to the image and extracting depth information through triangulation. The last technique involved laser point sensing. This method used a laser based measuring device to take as many points as necessary to establish the 3D image.

Image Processing

Vernon (1991) stated that "Image processing can be thought of as a transformation which takes an image into an image, i.e., it starts with an image and produces a modified (enhanced) image" (p. 44). This process did not attribute any values to the modified image and made no conclusion about the original or the modified image. MV used image processing to modify images which facilitated further analysis of that image.

Artificial Intelligence

According to Li (1990), 52 % of MV vendors considered AI as an integral part of MV, while the other 48 % felt that AI had no part in MV. If MV was a step above image processing, then MV must have exhibited some form of reasoning attribute (intelligence). Thus, it could be considered as a part of AI. However, the intelligence involved in the majority of current MV applications was trivial, which did give weight to the claim that MV was not part of AI. One could speculate that the reason some MV vendors did not want to associate their products with AI was because industrial vendors did not want to be linked to the many exaggerated promises of AI. However, to realize the full potential of MV, AI must be integrated with MV.

Industrial Applications of MV

Two common types of MV applications in the industry were inspection and control. Inspection consisted of applications that gathered the image data and made some determination concerning the status of the image. Control consisted of applications that gather images, make some determination concerning the status of the image, and supply feedback to regulate a manufacturing process.

Vision systems used for inspection applications did not provide feedback. They had no direct impact on manufacturing processes except through the intervention of the operator. Some categories of inspection applications were gauging, verification, counting, character recognition, identification, and flaw detection. Gauging consisted of measuring the distance between two points. Verification consisted of tasks that determine the correct placement of a component or the position of an opening. Counting consisted of determining the amount of something as in the number of products or the level of some material. Character recognition described the recognition of patterns/symbols to determine their meanings. It was useful in the inspection of labels, tags, etc. Identification consisted of recognizing an item that would normally require the presence of an inspector. Flaw detection detected the irregularities that exist in products like paint jobs, solder joints, and weld points.

Inspection applications. Robot Vision Systems, Inc. (3D inspection of solder joints, 1990) developed an inspection system that inspects solder joints in 3D. The HR-2000 system acquired the 3D information on the solder joint and analyzed this data using an expert system. It could detect defects in the areas of joint placement, wetting angles, solder volume, and fillet curvature.

Charette et al. (1988) developed an automated system that performed the 100% inspection of printed circuit boards. Their research emphasis was on developing a low cost micro-computer based image analysis system. Their PCB inspection system was based on dimensional verification and template matching.

Voyager 1000 from View Engineering measured with a linear accuracy within +/- 0.0002" and a repeatability of +/-0.00015" (Stovicek, 1993). It was simple to use and factory ready. The operator could measure anything in the FOV and set up the system for automatic inspection.

Control applications. Using machine vision for control was more complicated than inspection, because the task of control required a higher level of intelligence. This was the reason that MV control applications were not as numerous as inspection applications. Control applications consisted of material handling and robot guidance.

Material handling encompassed applications which used MV in the transportation/moving of resources. Applications in material handling included bin picking, sorting, and hazardous material handling. Robot control consisted of using MV to guide robots in industrial processes. Some applications were welding, cutting, and placing.

Forman (1985) described a MV controlled robot that depalletizes steel cylindrical billets. The MV system gathered the position information of billets on a pallet. It then guided the robot in picking up the billets and positioned it in a furnace. After the steel billet was heated, the robot moved the billet to a forging machine which pounded it into a turbine blade.

Brooks (1987) described a machine vision guided robot system (GMF robot using a GMF Grayscale Vision System) used by J. Lynmar Mfg. to perform hazardous material handling. The vision system guided the robot to pick up parts on a conveyer. It controlled up to four robots.

Robot System

Stonecipher (1989) provided a detailed description of robot systems. The following paragraphs summarized his descriptions.

A robot was an actuator used to manipulate or move objects. There were three types of actuator drivers: hydraulic, pneumatic, and electric. A robot controller usually consisted of a programmable micro-processor interfaced to the drivers. The robot performance measurements were dynamic capabilities, stability, spatial resolution, control accuracy, repeatability, and compliance. The joint-arm kinematics described ideal robot motion with respect to a fixed-reference-point coordinate system.

Actuator Drivers

Hydraulic actuator drivers used fluid pressure to move a cylinder attached to the actuator. Microprocessor controlled servovalves provided closed-loop feedback which enabled a high degree of power, accuracy and repeatability. The actuator oscillation problem with earlier hydraulic driver had been corrected by anticipation and adjusting to the "settling point." One disadvantage was that hydraulic drivers required a "warm-up period" before they could begin normal operation, due to the changes in fluid viscosity caused by an increase in temperature. Pneumatic actuator drivers used gas pressure to power their cylinders. Their advantages over the hydraulic drivers were that the pneumatic actuator drivers did not require fluids and warm-up period. However they were not as powerful as hydraulic drivers. Electric drivers utilized either stepper or servo motors to power the actuators. Their advantages were high accuracy and repeatability provided by closed-loop control. Because they operated on electric energy, these drivers did not require additional fluid or air pressure units.

Controller

The robot controller provided either closed-loop or open-loop control. Closed-loop control required constant positioning feedback from actuators. Open-loop control used limit switches to determine the home position. The close-loop control method offered robot systems greater accuracy and repeatability but required the installation of feedback sensors. The open-loop method controlled the position of the actuator by remembering the steps or pulses relative to the home position, so if the load changed then the established positions were lost. Converting the reference coordinate system to the work area of the robot required a large amount of processing power. For precise positioning of the robot, an embedded microcontroller might not have the power to map the robot reference coordinates into the real world positions of the robot work space.

Performance

Acceleration, deceleration, velocity, and drift were some of the measures of dynamic capabilities of a robot system. These qualities determined the cycle time required to perform a given operation. Robot stability described the degree of oscillation during robot operations. A high level of oscillation could prevent a robot system from reaching a steady state (stable condition). This increased wear, reduced repeatability, and lowered dynamic capability. Spatial resolution referred to the smallest movement of the end effector. This described the smallest movement controllable, not the smallest movement possible for a given actuator. Accuracy referred to the ability of the robot to move to a specified point regardless of the number of adjacent points. Repeatability referred to the robot's ability to return to a pre-defined position. Compliance referred to the force output of the end effector in relation to the applied force. High compliance meant that a small input force translated to a large output force. Low compliance meant that a large input force translated to a small output force.

Joint-Arm Kinematics

Joint-arm kinematics described robot movements. The degrees of freedom described the robot's ability to move in different directions. A robot that provided a vertical, a horizontal, and a rotational motion was said to have 3 degrees of freedom. Increasing the degrees of freedom increased the flexibility of the robot, but also increased kinematics calculations required. The basic reference coordinate systems described were cartesian, cylindrical, polar, and revolute coordinates.

> Cartesian coordinates are those which may be defined as formed by three mutually perpendicular linear axes, usually labeled as x, y, and z axes. Cylindrical coordinates are formed by two perpendicular linear axes, such as x, and y axes, and one rotary axis, such as a rotation about a z axis. The spherical or polar coordinate system is one where there is one linear axis, such as an x axis, and two rotary axes, such as rotations about the y and the z axes. The revolute or articulated coordinated system is one where the three axes are all rotary types of axes, such as rotation about the x, y, and z axes. (Stonecipher, 1989, p. 26)

Light Sources

Some common sources of illumination were the electric-discharge, the incandescent, and the electrolumescent lamps. Fluorescent light sources (a type of electric-discharge lamp) were the most commonly available light sources in the industry, and incandescent light sources were the second most common (DiLouie, 1994). The electric-discharge lamp was a diffused light source and produced light through an electric discharge and fluorescent. The incandescent lamp was a point light source and generated a light spectrum described by the hot bodies effect. The electrolumescent light source converted electric current directly into light through a gas.

Fluorescent Lamp

The fluorescent lamp produced light in two stages (DiLouie, 1994). An electric arc was first generated in the two electrodes. This arc produced a flash of high intensity ultraviolet radiation which excited the fluorescent chemicals coated on the inside of the lamp. The excited atoms returned to their normal state and gave off visible radiation in the process. By using different fluorescent materials, different types of fluorescent lamps produced different spectral power curves (see Appendix A). Some common fluorescent lamps were: cool white, deluxe cool white, warm white, deluxe warm white, white, and day light. The cool white was the most popular because it was one of the most efficient lamps produced, and its lighting effect was similar to that of natural outdoor lighting (Traister, 1974). One of the characteristics of fluorescent lamps were their ability to generate various light colors. Different color lamps produced different color rendering ability. The incandescent lamp had a rating of 100 CRI by definition. The F40/CW fluorescent lamps had a CRI around 65. The F32T8 trichromatic lamps had CRI as high as 85.

Vernon (1991) indicated that the fluorescent lamps provided the best lighting for machine vision systems. It was a diffuse light source, so the effects of shadows were less noticeable, and it was very energy efficient. AC powered lamps could cause a "flicker" effect. This effect might not be apparent to humans, but could cause a change in the image acquired by the vision system. When this effect occurs, a DC power supply should be used to alleviate this problem.

The "flicker" effect only pertained to traditional ballast that operates at 60 Hz. With the implementation of electronics ballast which operates at 25,000-60,000 Hz, this effect was not as obvious (DiLouie, 1994). Furthermore, the electronic ballast increased lamp efficiency (around 10%), reduced energy consumption (12-40%), reduced the number of ballast needed for multiple lamps, lowered weight, lowered noise, and increased ballast life.

Incandescent Lamp

Incandescent lamps produced light by passing a current through a filament (DiLouie, 1994). This current heated the filament to an incandescent which produced a continuous light spectrum (see Appendix A). Incandescent lamps had a CRI around 100. Because incandescent lamps produced light in a continuous spectrum, much of the energy was dissipated as IR energy (heat). This dissipation of electrical energy made incandescent lamps less efficient than fluorescent lamps.

Vernon (1991) described the incandescent light source as one of the simplest light sources to use. It was simple, cost effective, and easy to install. One of the major benefits was the ability to adjust and control its luminous flux. However, it was a point light source and provided directional illumination. This could generate shadows which might cause problems for vision systems. Another argument against the incandescent lamp was the degradation of its luminous flux with age. Lastly, it emitted a large amount of IR radiation. This posed no problems for human beings, but CCD cameras were particularly sensitive to IR.

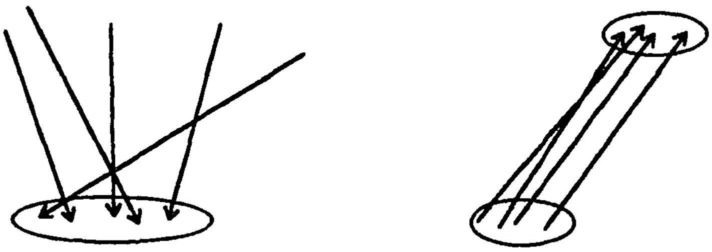
Electrolumescent Lamp

The electrolumescent lamp produced light by passing an electric current through a vapor and generated light directly (Traister, 1974). Its advantages were high lumen output, longer life, compactness, insensitivity to ambient temperature, and better control than fluorescent. However, it needed a long start up time, required a stable voltage, and had a low CRI.

Light and Brightness

Visible light consisted of a small portion of the total electromagnetic radiation spectrum. Various light sources generated different wavelengths in this spectrum. Four terms were used to describe the lighting condition in a surrounding that were more specific than the terms light intensity level or brightness.

Horn (1986) introduced the terms irradiance and radiance (see Figure 5). Irradiance was defined as the power per unit area of radiant energy falling on a surface. Radiance was the radiant energy emitted into a unit solid angle. In simpler terms, irradiance was the intensity of light or other forms of electromagnetic radiation falling on a surface, and radiance was the radiant energy emitted from a surface.



Irradiance: $E = \frac{\delta P}{\delta A}$ Radiance: $L = \frac{\delta^2 P}{\delta A \delta \omega}$

Figure 5. Irradiance and radiance. Irradiance: E denotes irradiance ; δP is the power of the radiant energy; δA is the infinitesimal surface area. Radiance: L denotes radiance; $\delta^2 P$ is the power emitted by δA into $\delta\omega$. (Horn, 1986)

DiLouie (1994) described two other terms which were similar to irradiance and radiance. Luminous flux was the light output from a lamp, and illuminance was the amount of light measured on an area. While irradiance and radiance included the entire electromagnetic spectrum, luminous flux and illuminance were generally referred to radiant energy in the visible light spectrum.

Computer Interfacing

Manufacturing has been transformed by the application of computer in the controlling of manufacturing processes. Some of the technologies were computer-integrated manufacturing, computer-aided manufacturing, and flexible manufacturing. The technological systems implemented were flexible manufacturing system, computer numerical control machine, and distributed numerical control system. These technologies and technological systems depended on the user's ability to interface computers to machines or processes. Thus, computer interfacing was an important topic in the area of manufacturing.

The introduction of integrated circuits (IC) based on the field-effect transistors (FET) in the 1970s revolutionized the way people process data. Although, faster bipolar computers already existed at that time, they were reserved for large organizations with the capital to invest in these expensive machines. At first, FET-based devices were not designed to be the general purpose central processing unit (CPU). These processors were designed to be programmable controllers. The economy of the FET devices drove down the cost of computers and made them available to the general population. Today, the computer industry has came full circle. PCs were considered a viable alternative to PLC in industrial applications. With the widely available-inexpensive PCs, it was feasible to use them to monitor and control industrial processes.

Components

The capabilities of any computer were based partly on the input/output (I/O) devices interfaced to it. Standard I/O devices were monitors, keyboards, printers, disk drives, and modems. While these standard interfaces were sufficient for the average end user, industrial applications required more specific interfacing. Some common types of industrial interfacing applications were DC servo motor control, pressure sensing, and temperature sensing.

There were many important components in computer interfacing. Some common components included: addressing, digital to analog (D/A) conversion, analog to digital (A/D) conversion, transducers, amplification, and programming.

Addressing. The computer addressed an I/O device by putting a selected sequence of bits (address) into the address bus. There were two common methods of I/O addressing: I/O mapping and memory mapping. I/O mapping used specific I/O instructions which accessed pre-defined I/O addresses, while memory mapping treated the I/O device as a regular memory location and accessed it through regular memory instructions.

Digital to analog conversion. The computer operated in a digital environment. Signals in the physical world did not. Thus, in order for the computer to output signals to some analog device, the digital signals needed to be converted into analog signals. The D/A converters were used for this purpose. Through the D/A device, digital data were converted into an analog signal.

Analog to digital conversion. On the other hand, analog input from the physical world needed to be converted into digital signals, before the computer can process it. This was done through the A/D converter. The A/D devices usually operated in a prescribed voltage or current range, so the analog inputs from the physical world needed to be pre-processed through an amplification device.

Transducers. Transducers were devices which converted dissimilar energies into electrical energies. The microphone converted the mechanical sound energy into electrical energy, and the temperature sensing diode converted heat energy into electrical currents. The electrical signal generated by the transducers were usually analog in nature and needed to be converted into digital signals using the A/D converter.

Amplification. The signals from the transducers were often not in a form readily translatable into the digital format. Some of the signals might be too small, so a positive amplification needed to be performed before inputting to the A/D device. Other signals might be too large, so negative amplification was required.

Programming. The coding complexity for I/O devices depended on the application, but some basic tasks were common in I/O programming. I/O devices usually required a command instruction that specified the configuration of that device. For example, to use the 8155 chip as an output device, an instruction word must be written into its command register (through specifying the command register address) which specified the I/O ports as outputs. Interrupt and polling methods were methods employed by the computer to process I/O requests. The interrupt method enabled the computer to proceed with normal operations until an I/O device requested a service. The polling method continuously monitored the I/O device for input and executed the predefined routine based on the pre-set conditions.

Industrial Applications

PC-based controlling and monitoring applications were becoming a viable industrial technology. According to Dr. Abdel Rahman (as cited in Babb, 1994), out of 100 customers surveyed over 70% expressed a desire to move from specialized control to open architecture control and 24% would choose PC-based units for their next generation of control. Some of the recent standards like the dynamic data exchange (DDE), object linking and embedding (OLE), and object database connectivity (ODBC) enabled data acquisition systems to import data into spread sheet software (Gerold, 1994). The Cutler-Hammer Industrial Control Div. of Eaton Corp. introduced a product which interfaced an I/O network of sensors and actuators to industrial software packages running on a PC. Cutler-Hammer also entered into a partnership with Ford to apply multiplexed I/O on the Ford Winsor Truck Modular Engine Program (Babb, 1994).

The FET-based processors had came to a full cycle by returning to industrial control application. As their cost decreased and functions expanded, PC-based controller had became a viable industrial technology.

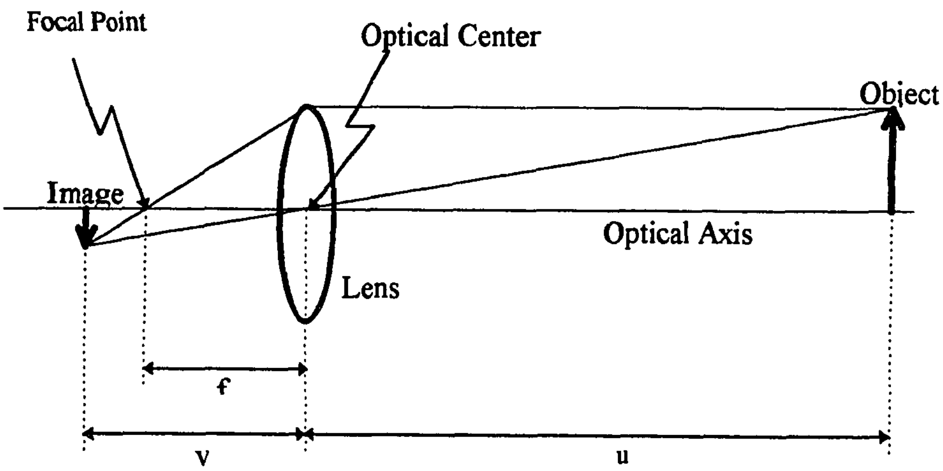
Image Acquisition

Image acquisition concerned itself with the transformation of the reflected illuminance from the scene into digitized images that could be processed by a computer.

Elements affecting the quality of this transformation included optics of the lens, sensors, and image formation.

<u>Optics</u>

Lenses were use to focus the radiance from the scene (Vernon, 1991). They were defined by their focal length and aperture. These parameters determined a lens's light gathering ability, magnification, and field of view (FOV). The basic Thin-Lens Equation described the relationship of the focal length f to the FOV in terms of the distance, v, from the lens to the scene and the distance, u. from the lens to the object (see Figure 6).



$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

<u>Figure 6.</u> Thin Lens Equation.

The magnification factor (M) was described by the following equations:

$$M = \frac{\text{image size}}{\text{object size}} = \frac{\text{image distance}}{\text{object distance}}$$

The relationship of the focal length and magnification is thus:

$$f = \frac{uM}{M + 1}$$

To understand and to apply these variables effectively, the following terms and concepts were used: (a) minimum focal distance, (b) f-number, and (c) depth of field. The minimum focal distance was the smallest distance from the front of the lens to the object while the object remains in focus. The f-number was a standard scale (1.4, 2, 2.8, 4, 5.6, 8, 11, and 16) for measuring the amount of light passing through the lens. Each increase in the f-number reduced the light throughput by one-half. The depth of field was the distance between the closest and the furthest points remaining in focus. If the f-number increased, then the depth of field increased.

Sensors

CCD cameras were the primary image acquisition input device used for machine vision. CCD was an acronym for charge coupled device (Stonecipher, 1989). Each CCD element contained a CCD cell and a sample and hold unit (see Figure 7). Light striking the CCD cell generated a leakage current that was proportional to the light

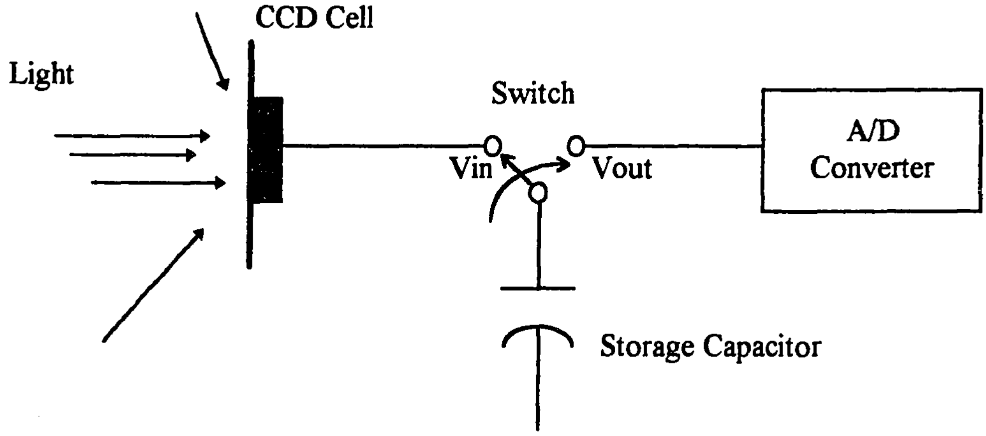


Figure 7. CCD cell, sample and hold circuit, and A/D converter.

intensity. A sample and hold circuit stored the current in a capacitor for a pre-set time interval. An A/D converter converted the electrical voltage output from the sample and hold unit into digital signals for the computer. Because the CCD cells were constructed on an IC wafer, small and rugged high resolution cameras were possible. Depending on the application, CCD camera manufacturers produced CCD matrix of varying dimensions (i.e., 512 by 512 or 1024 line sensor).

The more important characteristics of a machine vision sensor were resolution, geometric faults, sensitivity and transfer linearity, lag, spectral sensitivity, blooming, and noise (Vernon, 1991). The sensor resolution was the number of total pixels the camera could discriminate. The geometric fault of the CCD camera (usually due to the lens) produced a deviation in the vertical and horizontal displacement. The camera sensitivity and linearity described the relationship of how the input light distribution transferred into current or voltage output. The linearity of the CCD camera was 1. The spectral sensitivity was a function of how the sensor converted the various wavelengths of the incident light. If the camera's sensor was exposed to an intense light, then the excess charge carriers spread into adjacent regions and caused light to be registered there also. The camera noise consisted of the random interference on the video signal and was expressed as the signal-to-noise ratio.

Image Formation

An image formed by the CCD camera depended on the scene illuminance and the reflectance from the scene (Gonzalez & Brzakovic, 1989). If pixel in the image acquired by the CCD camera was represented by f(x,y), then the intensity level or the grayvalue of the f(x,y) depended on the intensity of the light striking the CCD cell. This intensity was a function of the illuminance on the scene and the reflective properties of the various objects in the scene. If r(x,y) equaled the reflectance component and i(x,y) equaled the illumination component, then the equation for f(x,y) was:

$$f(x,y) \quad = \quad [i(x,y)]\,[r(x,y)]$$

Thus, the image acquired consisted of an x by y matrix of f(x,y). The grayvalue of the f(x,y) equaled the product of i(x,y) and r (x,y).

Image Processing

Image processing operations transformed an image into another image for further analysis. Some common operations of image processing were point operations, neighborhood operations, geometric operations, and mathematical morphology (Vernon 1991).

Point Operations

Point operations were pixel level manipulation on a particular pixel. These operation were also referred to as grayscale operation. Contrast stretching, thresholding, image addition, and background subtraction were considered as point operations. Contrast stretching enhanced the contrast of an image by (a) shifting the left end point of the portion of the grayscale histogram desired to zero and (b) stretching the right end point of the portion of shifted image histogram desired to the highest grayvalue. Thresholding reduced a grayscale image to a binary image. Pixels with a grayvalue equal to or higher than the threshold value were set to 1, and pixels with a grayvalue less than the threshold value were zeroed. The threshold value was determined by evaluating the histogram of the image. Image addition reduced the noise level in images of the same scene taken at different times. Noises were randomly distributed in the image, so if the average of the noises (of several images) was zero, then the averaging of several images reduced the general noise level. Background subtraction reduced noise or detected motion in a scene. If there existed a known source of noise in a scene, then subtracting the noise from the scene reduced the noise level. By subtracting a previous image from the present image, stationary objects canceled out while moving objects remained.

Neighborhood Operations

Neighborhood operations transformed the grayvalues of a pixel in an image on the basis of the greyvalue of the pixel itself and the grey values of neighboring pixels. Convolution, low pass, thinning, erosion, and dilation filters served to perform the neighborhood operations. A convolution filter took the image function f(x,y) and convoluted it with the system characteristic function. Applying the appropriate filters enhanced or attenuated certain attributes of the image. Noises generally generated a high spatial frequency, so applying a low pass filter to an image reduced the noise level. Thinning filters removed pixels from the border of an object in an image. This was useful for skeleton generation, if the object and its background were known. Erosion filters took pixels from an object region, while dilation filters added pixels to an object region. Erosion and dilation filters were useful in fault determination and connectivity analysis.

Geometric Operations

Geometric operations transformed the spatial location of an image. Their application could correct geometric distortion and perform image registration. Spatial warping, spatial transformation, and grayvalue interpolation were methods for performing geometric operations. Spatial warping methods worked by applying a mathematical model equation to the targeted image and could remove distortions in that image. Spatial transformations worked by mapping pixels from one location in an image to another location. They were generally implemented through the application of polynomial functions. Grayvalue interpolations generated integer level pixel values for the image obtained from spatial operations and removed areas of sharply contrasted grayvalues.

Mathematical Morphology

Mathematical morphology consisted of operations that transformed an image based on mathematical set theories. These techniques could perform both image processing and image analysis functions. Morphological functions included hit or miss, erosion and dilation, opening and closing, and thinning transformations. Hit or miss transformations located regions in an image which matched the pre-defined structured elements and transformed the image accordingly. Morphological erosion involved the subtraction of the pre-defined structured elements from the image. Dilation was the erosion of the complement of the image. Morphological opening involved the consecutive morphological erosion and dilation of an image. Closing was the duel of opening or the consecutive morphological dilation and erosion of an image. Morphological thinning involved the subtraction of hits in the targeted image. This was useful in the identification of end points.

Image Analysis

The industrial applications of machine vision were primarily 2D in nature. The analysis of 2D images was concerned with the representation, description, and matching of images (Gonzalez & Brzakovic, 1989).

Representation

Representation described the process involving the extraction of scene details from a binary image. Chain codes, polygonal approximation, signatures, region skeleton, and convex are some of the methods used to obtain scene details. Chain codes represented boundaries by connecting a series of lines vectors. Polygonal approximations also represented boundary conditions by approximating the boundary of a particular object using a polygon. Signatures represented boundaries using one-dimensional functions. Skeletons represented an object in a region by reducing the structural shape of a region to a graph using thinning algorithms. Convex described the shapes in a region by using the convex hall and convex deficiency of the objects in that region.

Description

In order to use the information stored in an image, the proper description of the object must be extracted. Some object descriptors were length of a contour, diameter of a boundary, curvature of a boundary, shape number of a boundary, axis of a boundary, moments of a signature, area of a region, perimeter of a region, principle axes of a region, connected components, and moments of a region.

Matching

Once a set of descriptors was extracted from an image, one could identify an object in an acquired image by matching these descriptors to stored referenced descriptors of that object. Quantitative and structural methods were two approaches to matching. The quantitative approach compared the quantitative data of individual descriptors at a particular tolerance. Structural approach compared the interrelationship of the descriptors to each other.

Review of Pertinent Studies

Although lighting was often identified as an important variable which affects machine vision in vision related-literature, literature pertaining to its effects was scarce. The following were some of the more applicable sources concerning the effects of incandescent and fluorescent lighting on vision-based material handling.

Lighting could affect the performance of a vision system and different applications may require different types of illumination. Kovacevic et al. (1995) used a strobe-illumination unit to achieve vision control of a welding machine (the pulse laser provided the intensity need to compensate for the ARC welding). Others used illumination techniques (structured lighting) to obtain depth information from one 2-D camera (Chen & Tsui, 1989; Kinoshita & Idesawa, 1985; Wolff & Fan, 1994).

According to Vernon (1991), diffuse lighting was more suitable for most machine vision applications, because it was non-directional and produced a minimum amount of shadows. Incandescent lighting was less suitable for machine vision, because it was generally a point light source which cast strong shadows, and it emitted a considerable amount of infra-red radiation which could adversely affect CCD cameras. He also indicated that using AC powered light sources could introduce "flicker" in acquired images and that DC powered light source could alleviate this problem.

Ward, Rossol, Holland, and Dewar (1981) described a vision material handling system which uses a linear CCD array to identify object positions for the robot to pick up from a moving conveyor. The illumination of the part was provided by a tungsten bulb with a cylindrical lens that projected an intense line of light across the belt surface. However, the objects could obstruct the light before it reached the FOV scanned by the linear array. This problem was solved by using multiple light sources directing a narrow strip of iiluminance across the same belt surface. This essentially solved the problem due to the "shadowing" effect.

Review of Related Patents

In a 1987 Wandell and Maloney were awarded U.S. Pat. No. 4,648,051 for a method that separates the effects of ambient lighting from the effects of surface reflectance. This method could be used to analyze and determine the surface properties of the material. It measured the true color of the material by estimating the spectral reflectance of surfaces, and relative spectral power of the ambient light. This method was similar to the human ability to discount the spectral variation caused by different illuminants. This apparatus measured true color by estimating the relative spectral power of the ambient light based on the changes in surface reflectance due to constant illumination of the surfaces and surface reflectance changes in a relatively small region.

Funt, Ho, and Drew were awarded a 1991 patent, U.S. Pat. No. 4,992,963, for a method and apparatus for determining ambient light and surface reflectance. This apparatus divided light reflected by an illuminated surface into two parts: illuminating light and surface spectral reflectance of the surface. This invention operated by generating a set of weighting coefficients for each of the illuminant basis functions and comparing it to a generated set of weighting coefficients for the illuminating source. This apparatus compared the illuminance and reflectance in one point and did not require the spectral reflectance or the illuminance on the said surface to be constant. This apparatus was developed to mirror humankind's natural ability to determine the color of a given surface under a variety of different lighting conditions. This invention differed from the previous invention by Wandell and Maloney by only viewing the surface spectral reflectance at one point and estimating the ambient light at that point.

Arima and Takata were awarded a 1992 patent, U.S. Pat. No. 5,168,155, for a color measuring apparatus with flash lamp color temperature measurement. This apparatus emitted two flashes of light at an interval so that a detector that received the first flash of light could use it as a reference and compensate the received signal generated by the second flash of light. The values were compared with an ideal light source according to the signaled generated by the flash lights. This provided a means for measuring the light intensity of the target's color temperature.

Summary

Machine vision has played an increasing role in factory automation. One of the problems with the application of machine vision was scene illuminance. An examination of the literature produced little information on the effects of light sources or procedure and method that could assist developers in the selection of light sources. However, Vernon did indicate that incandescent lighting was inferior to fluorescent lighting and that DC sources reduced the “flicker” effect due to AC line voltage. Another study revealed the application of a special lighting setup which focused light into a line that fell across the conveyor. However, it did not sort colors. An examination of patents revealed several methods used to distinguish color. The common theme was the use of a reference light source to extract the color of the objects.

CHAPTER III

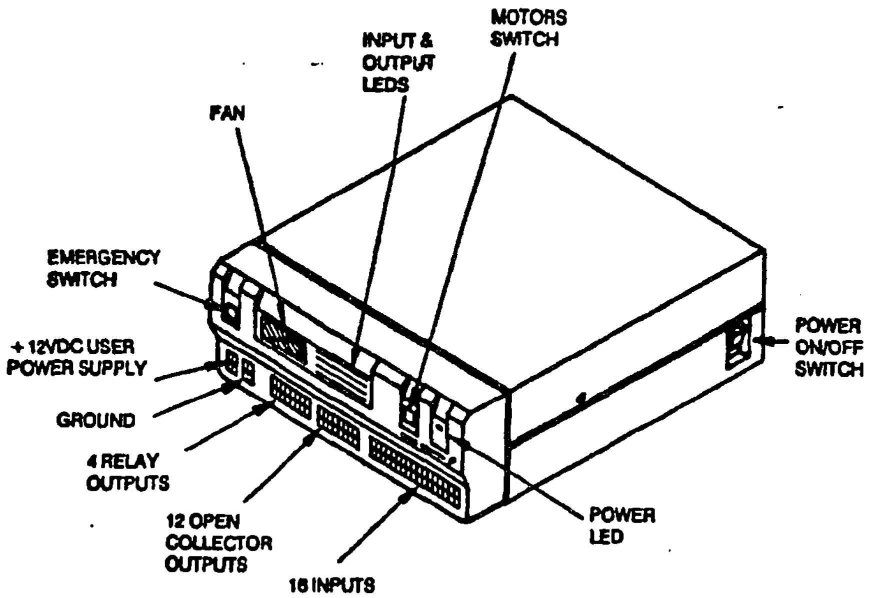
EXPERIMENTAL METHODS AND PROCEDURES

This study focused on the development of computer vision-based robot material handling applications involving the sorting and the "pick and place" of two different color parts from a moving conveyor under fluorescent and incandescent light sources. This chapter describes the components in this system, the process of developing the material handling system, the developed application, and procedures and methods used in this study

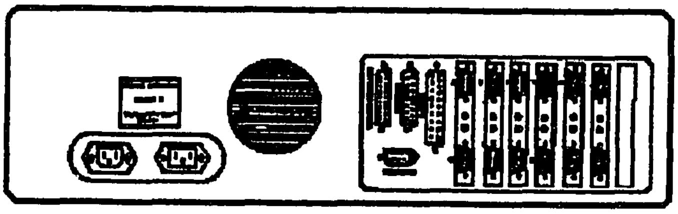
The Robot System

The SCROBOT-ER V plus (Eshed Robotec) was an IBM PC compatible computer controlled robot system. The system included a robot arm with a slide base, a robot controller, a conveyor, and a teach pendent.

The controller was capable of multitasking operation and stand-alone operation (see Figure 8). It provided outputs for 8 servo axes (standard) and the outputs could be divided into two groups for independent control and operation. The output drive signal consisted of a 20 kHz pulse width modulation that provided control for linear or circular point-to-point continuous path. The CPU for the controller was a Motorola 6810 CPU with 284K of EPROM, 64K work RAM, and 128 battery backed-up user RAM. It could be programmed using the ROBOTVISIONplus software. The controller also provided 16 input ports and 16 output ports. Other features included sensor interrupt



(a): Front view



(b): Rear view

Figure 8. Controller. (a): Front and side view. (b): Rear view. (SCROBOT-ER V plus user's manual, p. 1-12.)

capability, emergency brake switch, current limit on each axis, automatic fuse on each axis, user definable impact, thermal, and range limit protection (see Figure 9).

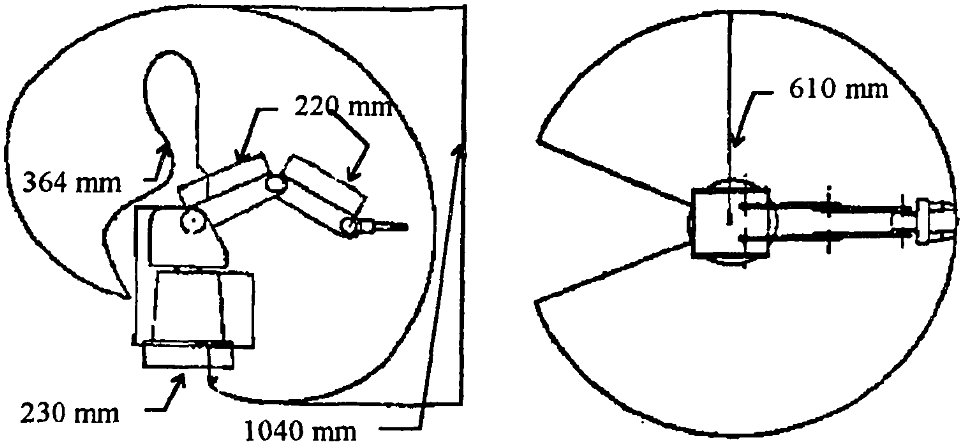


Figure 9. Robot range limit diagram. (SCROBOT-ER V plus user's manual, p. 1-8)

The robot arm had a vertically articulated structure and provided 5 degrees of freedom plus gripper (see Figure 10). The robot arm was mounted on a slide base which provided it with one additional degree of freedom. DC servo motors powered all the robot axes, provided a torque of 15 oz.in, and used 70W for peak torque. These motors used optical encoders for position feedback and limit switches to define the robot's home position. Other interesting features were 1 kg maximum workload, ±0.5 mm repeatability, 600 mm/sec maximum path velocity and programmable gripper displacement and force.

The orange conveyor (speed controlled) was compatible with the robot controller and ROBOTVISIONplus (see Figure 11). It was controlled by the axis 8 DC servo motor output and provided position feedback through an optical encoder. It measured 810 mm long and 100 mm wide. The PVC belt was driven by a servo motor with a gear ratio of 65.5:1.

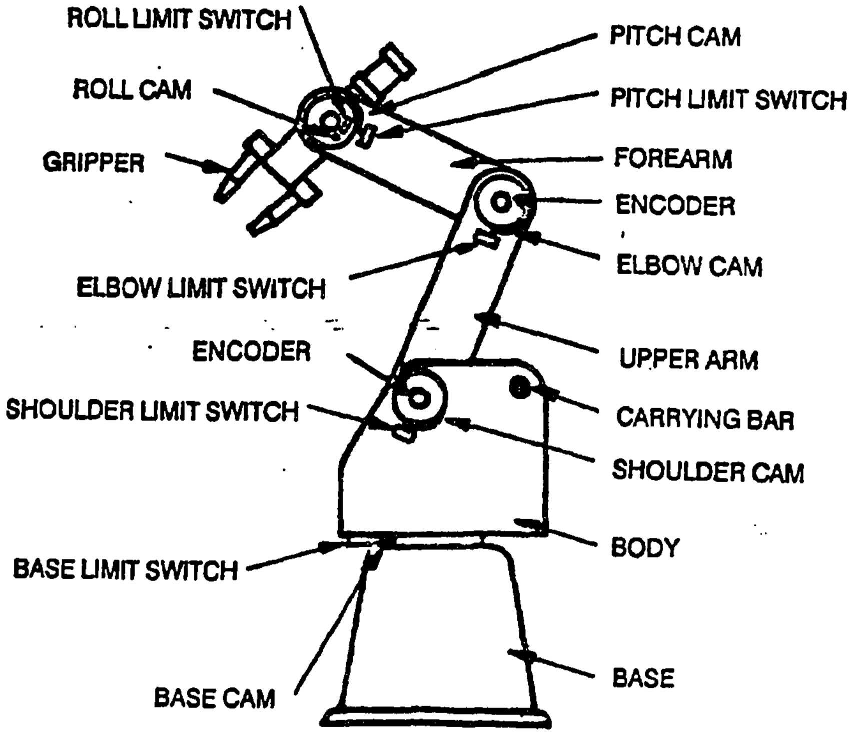


Figure 10. Robot arm view with parts and limit switches identified. (SCROBOT-ER V plus user's manual, p. 1-3)

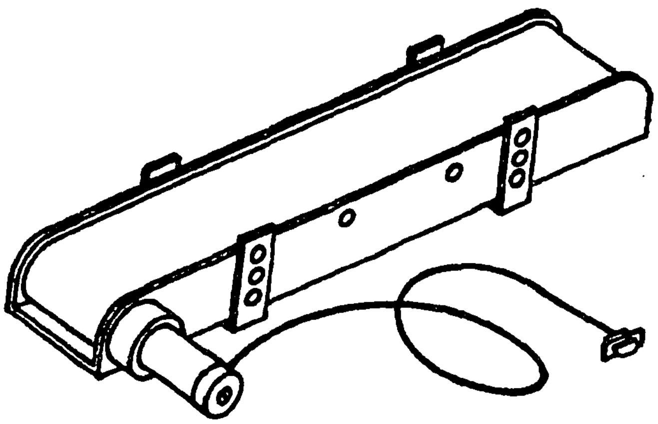


Figure 11. Orange conveyor. (SCROBOT-ER V plus user's manual, p. I-1)

The teach pendent allowed for direct manual operation and control (see Figure 12). With this pendent the user could specify the coordinate systems used by the controller, change the robot speed, enable/disable control, record positions, erase positions, go to positions, run programs, abort any currently running program, and stop movements on all axis.

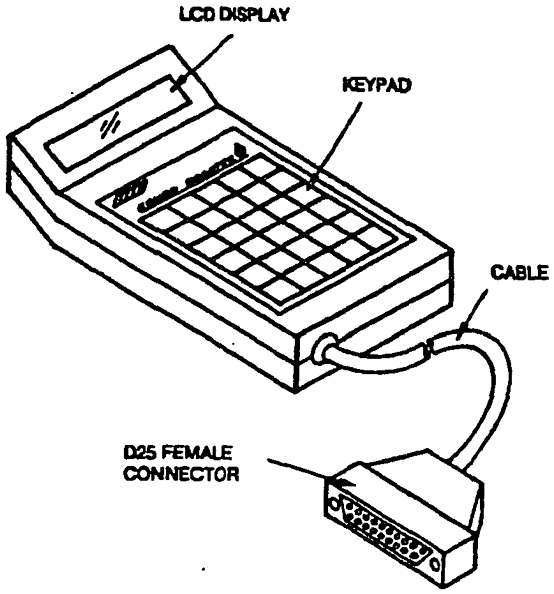


Figure 12. Teach pendent. (SCROBOT-ER V plus user's manual, p. 1-14)

The Vision System

The ROBOTVISIONplus was an integrated vision system compatible with the SCROBOT-ER V plus robot system (ROBOTVISIONplus vision system user's manual). It included a frame grabber, a camera and monitor, and the ROBOTVISIONplus software package. The frame grabber was capable of real time image acquisition at 30 frames/second. The system supported 4 different frames and 4 different cameras. The RS170 black and white camera with 16 mm lens and iris provided two resolution settings with 256 grayvalues. The low resolution setting provided a resolution of 256 x 242. The high resolution setting provided a 512 X 484 resolution. The RS170 composite monitor could display live, still, and digital images.

The ROBOTVISIONplus software provided an integrated environment where users could directly control or write programs to control the robot controller. This software provided a menu driven user interface. The menu was divided into the following modules:

1. VISION CONTROL
2. ROBOT CONTROL
3. ROBOT TO VISION SYNCHRONIZING
4. APPLICATION FILE MANAGER

<u>Vision Control Module</u>

The VISION CONTROL MODULE enabled the user to set up various vision settings used during run time. This module contained the following screens: camera set up, global set up, robot sync, histogram set up, filter set up, file manager, mode set up, database manager, identification set up, reference set up, and vision action.

The CAMERA SETUP SCREEN allowed the user to define the frame size, frame offset, gain and offset, and resolution. The user could view the live or frozen image of the FOV and save the picture onto the hard drive.

The GLOBAL SETUP SCREEN enabled the user to define the global vision action carried out in all the camera and frames. The user could choose the following vision actions: segment the picture, find object's center of gravity, computer shape parameters, compute extensive shape parameters, sizes normalize the parameters, and analyze holes. The user could also set the minimum and maximum size of objects and set up the orientation attributes of the object.

The MODE SETUP SCREEN allowed the user to define the mode of the vision system operation. In this screen the user could choose the following options: image input source, automatic file reload, picture file name, operation mode, screen report, beep on identification, show picture while operating, and show object's description table. The user could also load the picture file of interest and preview it.

The FILE MANAGER SCREEN enabled the user to load and to save various vision related files. The user could choose to perform the following actions: load/save set up, database, picture, synchronization files.

The HISTOGRAM SETUP SCREEN allowed the user to set up the camera and runtime parameters, to view live/frozen image, to view binary image, to change the threshold, to view histogram, and to view accumulated histogram. It could suggest threshold based on the histogram analysis and the accumulated histogram analysis. The user could also define the object to be brighter or darker than the background in this screen.

The FILTER SETUP SCREEN enabled the user to view and test the various filters available in the vision system. The user could set up the camera, view live or frozen images, and set the run time filter parameters. The filters available were the edge, binary smooth, erose, dilate, low pass grey, low pass, and high pass filters.

The DATABASE MANAGER SCREEN allowed the user to access, control, and manipulate the system's vision database. The user could perform the following actions in this screen: load database, save database, clear database, print database, view database, view entry, change entry, delete entry and view current entry.

The IDENTIFICATION SETUP SCREEN enabled the user to load, change, and save the vision identification setup. In this screen the user could choose which identification search method to use and specify the parameters and the tolerances used in the identification procedure. The types of parameters were surface area, perimeter length, shape, and hole parameters.

The REFERENCE SETUP SCREEN allowed the user to define reference image use in vision operations. In this screen the user could take, save and view a reference image. The user could also perform image addition, image difference, AND, OR, XOR, operations using the reference image.

The VISION ACTION SCREEN enabled the user to perform vision actions including learn object, identify object, and overview. The user could choose to run the vision operation once, n times, or continuously.

Robot Control Module

This module provided the user with the following functions: keyboard robot control, program development, and robot related file handling. The screens available in this module consisted of: teach positions, program handling, home, edit program, and run program screens.

The TEACH POSITION SCREEN allowed the user to move the robot, record robot positions, change the coordinate display system, and perform simple vision commands. There were two menus in this screen and the user could start each by using the left arrow for the left menu, and the right arrow for the right menu.

The PROGRAM HANDLING SCREEN enabled the user to load, save, delete, and list robot related programs. It also allowed the user to set the working directory of robot programs.

The HOME SCREEN enabled the user to move the robot, home the robot, define gripper sensor, and set up peripheral equipment. This was also the only screen where the user could select the speed for the conveyor within ROBOTVISIONplus.

The EDIT PROGRAM SCREEN allowed the user to create simple, but powerful robot-vision routines. To write a program, the user simply typed in the letters corresponding to the robot or vision commands desired, selected the appropriate operation, and entered the desired data. The user could also modify the program by inserting, replacing, or deleting lines.

The RUN PROGRAM SCREEN enabled the user to run the program. It was similar to the systems basic run screen, but did not display all the vision features. The user could step through the program lines, jump to a different line number, and stop program execution.

Robot to Vision Synchronization Module

This module enabled the user to synchronize the robot and the conveyor with the vision system. In this module, the user could load, save, and define synchronization parameters. It allowed the user to move the robot, take robot points, and take vision points. For conveyor synchronization, a sub-screen was deployed to let the user perform conveyor synchronization.

Robot-Vision System Operation

The vision system recognized an object by comparing the parameters stored in the object parameter database to the parameters of the part that was being identified. The object parameters were stored into the database by scanning it with the vision system under the "LEARN" mode. Then the user supplied the vision database with an object name and an object ID. In the “IDENTIFY” mode, if the parameters used to identify the objects were within in the tolerance level specified by the user, then the vision system output a beep and labeled the object as being the object name and object ID that was previously given by the user. Once the vision system correctly identified the object, it directed the robot to the coordinates of the object based on the translation values predetermined by the synchronization process. Because the robot needed to pick up the object from a moving conveyor, the conveyor synchronization was also performed.

Incandescent Lamp Light Intensity Controller

The incandescent lamp light intensity controller was constructed using a rotary dimmer, a stepper motor, and the Microbot's Motor Mover. It provided closed-loop control using the DX-200. The incandescent light intensity controller was interfaced to a 286 PC that served as the controlling unit.

The rotary dimmer was an off-the-shelf incandescent light dimmer by True Value hardware store. Its features includes: single pole, push on/off, rated at 600W-120VAC, incandescent only. The rotary dial had a rotation range of 290° (see Figure 13).

The unipolor stepper motor, PH264-02B, was manufactured by Oriental Motor company. Its features included: 30 Ω resistance, 12V DC at 0.4A, 1.8° step angle. This provided the controller with the ability to generate a maximum of 161 light intensity levels at 5 lux per level.

The Motor Mover was a micro-processor based motor controller produced by Microbot. It could control stepper motors and input and output ports. Its features included: serial interface capability, 6 stepper motor control ports, 7 inputs, and 5 outputs.

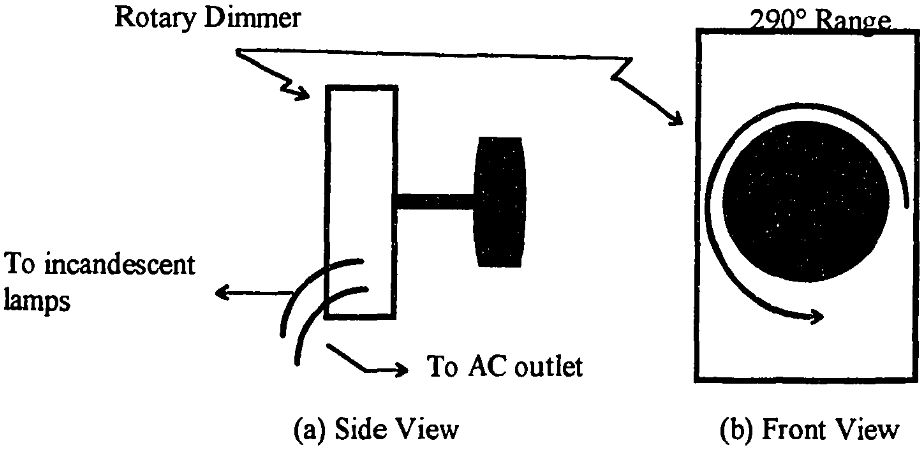


Figure 13. Rotary dimmer. (a) Side view. (b) Front view.

The IBM PS/2 used in this study contained 1Mb RAM, 80Mb HD, 2 serial ports, and a 1.44 floppy disk drive. The software used to code the control program was QBASIC. This program could accept either the input from the ROBOTVISIONplus or the DX-200 illumination meter.

Illumination Meter

The DX-200 digital illumination meter had (a) measuring range of 0 ~ 200,000 lux, (b) resolution of 1 lux from 200 lux up, and (c) accuracy of ±2% of reading ±1 digit. It had a response time of approximately 0.3 seconds and a 0 ~ 2V DC output at 1mV/digit (DX-200 Operation Manual). The recommended illumination for a factory is presented in Table 2. The unit conversion for illuminance is presented in Table 3.

Table 2

Recommended Illumination for a Factory

Locations	LUX
Packing work	150-300
Entrance passage	150-300
Visual work at production line	450-750
Inspection work	800-1200
Electronic parts assembly line	1500-2500

Table 3

Unit Conversion Table for Illuminance

LUX	PHOTO lx(lm/m^2)	FOOT-CANDLE ph(lm/m^2)	WATT PER SQUARE fc(lm/ft^2)
1	1.000×10^{-4}	9.290×10^{-2}	5.0×10^{-4}
1.000×10^{-4}	1	9.290×10^{2}	5.0×10^{-2}
1.076×10^{1}	1.076×10^{-3}	1	5.0×10^{-5}
2.000×10^{5}	2.000×10^{1}	1.900×10^{4}	1

Note. Total irradiance by the CIE standard light source "A".

Experimental Procedures and Methods

This study used pre-established procedures and methods when available. The followings were procedures and methods used:

Illuminance Measurement (DiLouie, 1994)

1. Turn fluorescent light on and allow 20 minutes for it to stabilize. Illumination of incandescent light sources can be measured immediately.

2. Eliminate the effects of extraneous light sources.

3. Position the light meter horizontally on the work plane (conveyor belt).

4. Record light level.

Surface Reflectance Measurement (DiLouie, 1994)

1. Hold light meter flat against the surface being measured and record light level. This measures the incident light level.

2. Hold light meter 1-1/2 feet away from the surface with the sensor parallel to and facing the surface being measured. Record light level.

3. Calculate surface reflectance.

Reflectance = Reflected light level / Incident light level

Measuring Procedure for the DX-200 (DX-200 operating manual)

1. Connect photo sensor to instrument.

2. Hold the sensor stationary during measuring.

3. Press <LUX/FC> key to change unit of measurement.

4. The DX-200 has an AUTO RANGE function which will display the range on the display.

5. Press the <HOLD> key to keep the measurement data temporarily.

6. Turn off light meter when done.

Selecting Threshold

For an ideal situation where the object and the background were of uniform brightness, the selection of a threshold would be the average of the two grayvalues (Horn, 1986). In practice, the pixels corresponding to the same object would not have the same grayvalue due to noise, sensor variations, and reflectance variation. In this case, a histogram of the grayvalues could be used to determine the best threshold. Ideally, a gap between the peaks enabled the threshold to be placed, but even when the two histogram peaks overlapped, a minimum could still be chosen as the threshold.

Although Vernon (1991) did not present a method to determine the threshold value, he provided two examples of selecting the probable threshold using a histogram. In one application of the histogram, he demonstrated the successful separation of PCB board pixels from solder pixels. In the other example, he used a histogram to threshold a grayvalue image of concentric circles to make the circles more visible.

The ROBOTVISIONplus provided the peaks and limits of a histogram. By choosing the threshold above the highest of the histogram limits, the user could obtain the optimal threshold. The optimal gain and threshold settings could be determined using the data collected from the stationary conveyor. The threshold values were set for each gin at 5 grayvalues above the highest background histogram limit. This provided better separation of objects from the background.

Camera Distortion Determination and Adjustment

A certain level of the camera's geometric distortion was inevitable. The camera was pre-adjusted before shipping (ROBOTVISIONplus vision system user's manual). The procedures for determining and adjusting the camera's geometric distortion were:

1. Set up ROBOTVISIONplus System
2. Mount the camera faced down at 90° to a dark surface.
3. Place a bright round object (COIN) in the center of the FOV.
4. Load setup configuration file "COMTEST" into system.
5. Look at the histogram and adjust the threshold until a good image of the coin appears.
6. Press <F1> in the vision action screen.
7. If the XWIDTH and the YWIDTH differ more than one, the camera needs adjusting.
8. If adjustment is needed, follow these instructions:
    a. Open camera cover
    b. Locate the POTENTIOMETERS that control the horizontal and the vertical proportions of the camera's output image.
    c. Adjust the POTENTIOMETERS until XWIDTH = YWIDTH
9. Press <ENTER>. Return to VISION ACTION screen.

Synchronization Procedures (ROBOTVISIONplus user's manual)

The synchronization of the robot, vision system, and the conveyor enabled the material handling system to pick an object from a moving conveyor. The prerequisites and procedures were as follows:

1. Prerequisites
   a. Position the camera (vertically) to view the robot's working area and the conveyor belt.
   b. The object used to synchronize the camera is analyzed and stored in the object database.
   c. The robot is internally synchronized through the homing process.
   d. The speed controlled conveyor must be properly configured.
   e. Set camera resolution to LOW RESOLUTION.
3. Robot-Vision Synchronization procedures
   a. Enter the vision sync module.
   b. Place the synchronizing object under the camera.
   c. Move the robot to the location of the synchronizing object.
   d. Use the robot gripper to grip the object, and make sure the pitch is -90.0 degrees.
   e. Take first robot point (F3).
   f. Open gripper.
   g. Move the robot out of the camera's FOV (Do not move the object).

h. Take first vision point (F7).

i. Move the object to another location in the FOV.

j. Move the robot to the location of the synchronizing object.

k. Use the robot gripper to grip the object, and make sure the pitch is -90.0 degrees.

l. Take second robot point (F4).

m. Open gripper.

n. Move the robot out of the camera's FOV (Do not move the object).

o. Take second vision point (F8).

p. Press (F10) to synchronize

q. If message box contains 'ERR in SYNC!', then check the prerequisites and the synchronization procedures and make sure they are followed.

r. If message box contains: ROBOT ↔ VISION SYNC OK !, then the robot is synchronized with the vision system.

3. Conveyor Synchronization Procedures

   a. The robot-vision system must be synchronized.

   b. Enter CONVEYOR SYN sub-screen by pressing (F9).

   c. Specify the desired speed (mm/sec).

   d. Specify the ID of the synchronizing object.

   f. Place the object in the edge of the conveyor.

   g. Press (F10) to start conveyor synchronization.

h. If synchronization is successful, then the screen will display the actual speed measured.

i. If synchronization is unsuccessful, the screen will display the respective error message.

j. If conveyor synchronization is unsuccessful, then repeat the synchronization process.

k. Save synchronization parameters (pressing F2).

Motor Mover Control

The Motor Mover could be programmed and controlled through any RS-232C serial port of a PC or a MAC (Motor Mover user's manual, 1987). This serial control required the following: (a) serial port configuration, (b) serial interface commands programming, (c) QBASIC programming.

Configuring the serial port. The Motor Mover could accept commands from the serial ports of the 286 PC. The procedures for configuring the serial port were:

1. Connect the RS232-C port of the PC to that of the Motor Mover (see Figure 14)

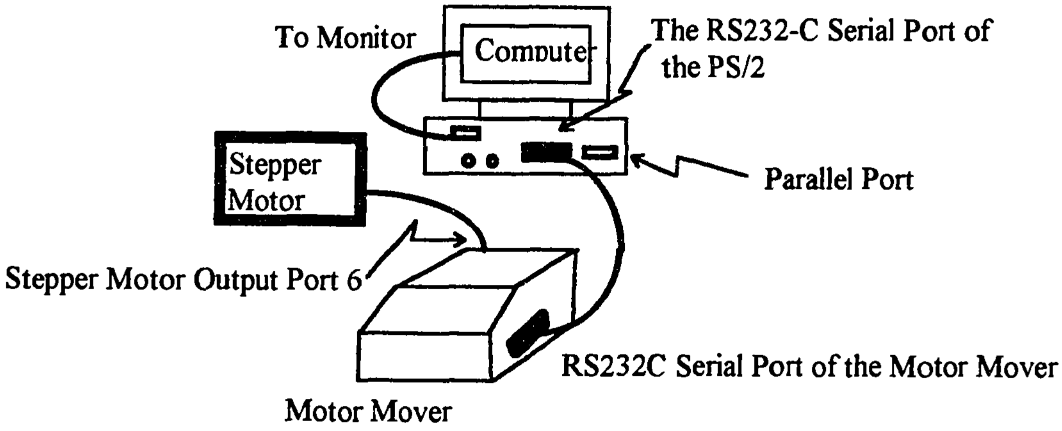
2. Set transmission rate to 9600 baud for both send and receive.

3. Use the following port data format

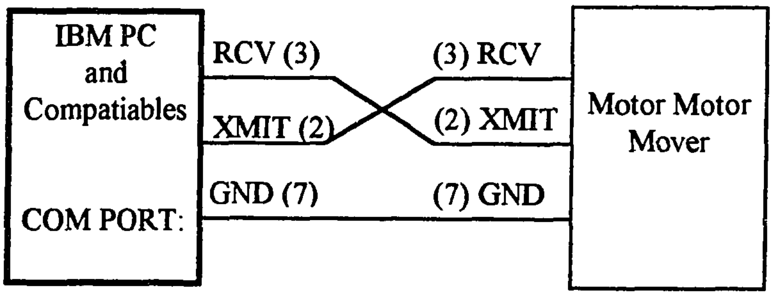
   a. Word length = 8 bits

   b. 1 start bit

   c. 1 stop bit



(a): Equipment setup diagram



(b): Serial port connection to the host computer

Figure 14. Serial port connection. (a): Equipment setup diagram. (b): Serial port connection to the host computer.

d. No parity bit

e. Full duplex

4. Opening the port -- consult individual PC manual.

5. Testing the configuration by sending out a @STEP 200, 100 command.

Serial interface commands. The two serial interface commands used to control the Motor Mover were the STEP and the READ commands. The STEP command was used to control the outputs to the stepper motors and the output ports. The READ command was used to read the internal position registers of the stepper motors and the values of the input ports.

The STEP command controlled the outputs to 6 stepper motor, 2 AC outputs, and 3 TTL outputs. The format of the STEP command was:

@STEP Speed, Motor_1, Motor_2, Motor_3, Motor_4, Motor_5, Motor_6, Output

Where:

Speed	=	Motor Speed (0-245)
Motor 1	=	Motor 1 steps
Motor_2	=	Motor 2 steps
Motor_3	=	Motor 3 steps
Motor_4	=	Motor 4 steps
Motor_5	=	Motor 5 steps
Motor_6	=	Motor 6 steps
Output	=	Binary output bits

The speed value was related to motor speed by the following formula:

$$\text{Motor speed} = \frac{1843200}{256(256\text{-Speed})}$$

The output value (1-256) was converted into 9 bits binary word with each bit controlling a particular output (see Table 4).

The user accessed the Motor Mover's input ports by using the READ command. This command returned the values of the Motor Mover's 6 internal position registers, value of the last key pressed, and an input byte. Table 5 contains the bit value assignments of the input byte.

Color Sorting Method

The quality of the greyscale image acquired by the camera depended on the light source's light spectrum distribution, reflective properties of the object and the relative response of the camera (Horn, 1986). The spectrum of the illuminance in the camera's FOV determined the amount of available light to be reflected. The illuminance into the camera from the FOV depended on the reflective properties of the object and the illuminance on the FOV. Thus, for a white object with reflectivity, r, the reflected

Table 4

Output Value Assignments

Binary output	Output Controlled	Output value
0	MODE light	1
1	AC output 1	2
2	AC output 2	4
3	TTL output 3	8
4	TTL output 4	16
5	TTL output 5	32
6	TRAIN light	64
7	RUN light	128
8	ENTER light	256

Table 5

Input Data Values and Functions

Input Byte Decimal Value	Function
0	Safety Barrier Closed
1	All Switches Open
2	Input 1 is Closed
4	Input 2 is Closed
8	Input 3 is Closed
16	Input 4 is Closed
32	Input 5 is Closed
64	Input 6 is Closed
127	Input 7 is Closed

illuminance would be greater than a red object with the same reflectivity. If the reflected illuminance was greater, then the CCD cell would produce a higher grayvalue. This could cause the camera to experience more of the "blooming" effect, and the white object would appear to be larger than the red object. This method was not limited to color sorting and detection and could be generalized into the detection of parts with different reflective properties.

Two methods were used in the development of the sorting applications. The first approach, Method A, was developed by applying the principles described by Horn (1986). This method separated the colors based on the principle that objects with higher reflectance appeared larger to the vision system than objects with lower reflectance. The second approach, Method B, was developed after Method A failed to achieve an acceptable performance level. This method separated colors by applying the principle that objects with higher reflectance would generate a higher grayvalue than objects with lower reflectance.

Method A sorted colors by comparing object descriptors. The vision system identified objects by matching the stored descriptors with the extracted descriptors of the current object in the FOV. The system produced a match, if the value of the current object's descriptors fell within the range set by the stored values of the descriptors and the pre-set tolerances (see Figure 15).

Method B sorted color by utilizing the "saturation" region of the camera's response to changing illuminance. The changes in grayvalues of the dominos and the background stabilized and leveled off after 300 lux. The region where the grayvalues are relatively stable (unchanged) was designated as the "saturation" region. This region covered 300 to 1300 lux for incandescent and 300 to 800 lux for the fluorescent lighting. This higher end of the "saturation" region was not yet defined, because the values given were limited by the illumination generated by existing light sources. By plotting the

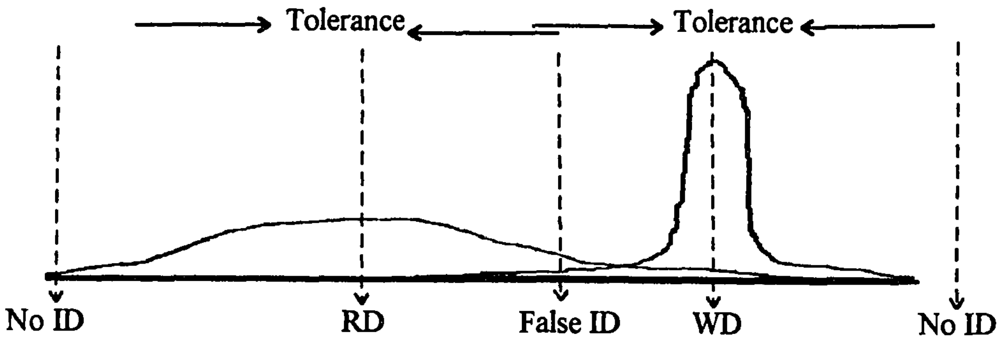


Figure 15. Color sorting results using Method A. No ID = no identification; RD = red domino; WD = white domino; False ID = false identification.

changes in grayvalues of the histogram peaks and limits over gain and illumination ranges, appropriate threshold values were determined.

Method B suggested that the vision system will falsely identify white dominos when the illumination drops below the point which the vision system registered that grayvalue for the white domino. At this point white dominos appeared to be red dominos. The sorting also failed when the illumination rose above the point at which the background was identified as red dominos or that red dominos were identified as the white domino.

Illumination Control Method

The illumination could be controlled using the voltage output from the DX-200 illumination meter. The illumination voltage output from the DX-200 was fed into an A/D converter. The A/D converter converted the analog voltage into digital signals. The program then converted it into a lux value. In addition, the light intensity control software compared the incandescent illuminance with the fluorescent illuminance (540 lux) and determined the appropriate output to the Motor Mover. Based on this feedback, the Motor Mover moved the stepper motor to adjust the luminance flux of the incandescent lamps.

Sorting Application Development

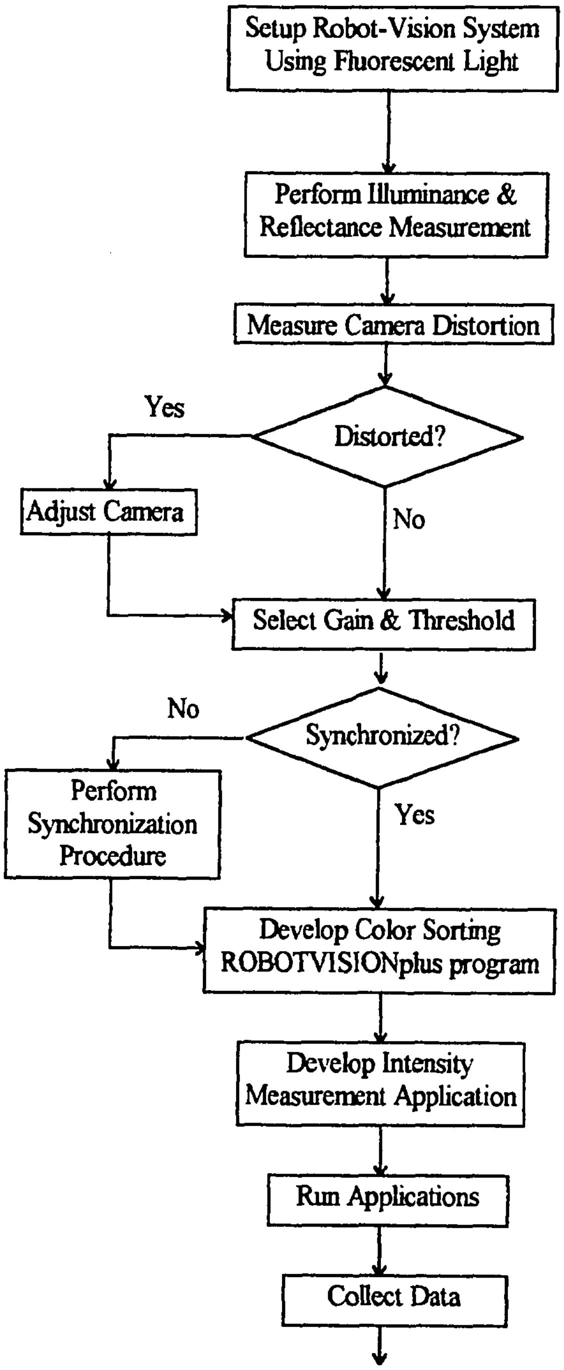
An application for the unloading of parts from a moving conveyor was developed. The robot picked up the parts, placed them on the conveyor, and unloaded the parts. The vision system identified the parts on the moving conveyor and sent the appropriate control signals to the robot to pick up the parts. It also included a data collection subroutine to automatically collect the data for analysis. The light intensity level was controlled by adjusting the light level sensitivity of the incandescent light to match that of the fluorescent light source.

Steps in System Development

The steps taken in the development of this application were: (a) characterizing the robot vision material handling system, (b) positioning components, (c) analyzing methods for sorting of color, (d) developing application software, (e) collecting data, and (f) analyzing performance. Due to the variety of variables and the complexity of the application a guideline for application was needed. A flow chart of research procedures and steps used was developed to provide a general structure to follow in the system development process (see Figure 16).

Population

The system performance sample data were taken from the developed material handling sorting application with a population of 5 red dominos and 5 white dominos with their undotted sides up. One batch of data consisted of the success and failure sequences of sorting operations on the population. The dominos measured 2.5 by 1.44 by 0.45 mm. The area of the undotted side was calculated as 3.6 mm^2. The perimeter of the domino measured 7.88 mm. The actual pixel values would depend on the gain, threshold, and illuminance.



(figure continues)

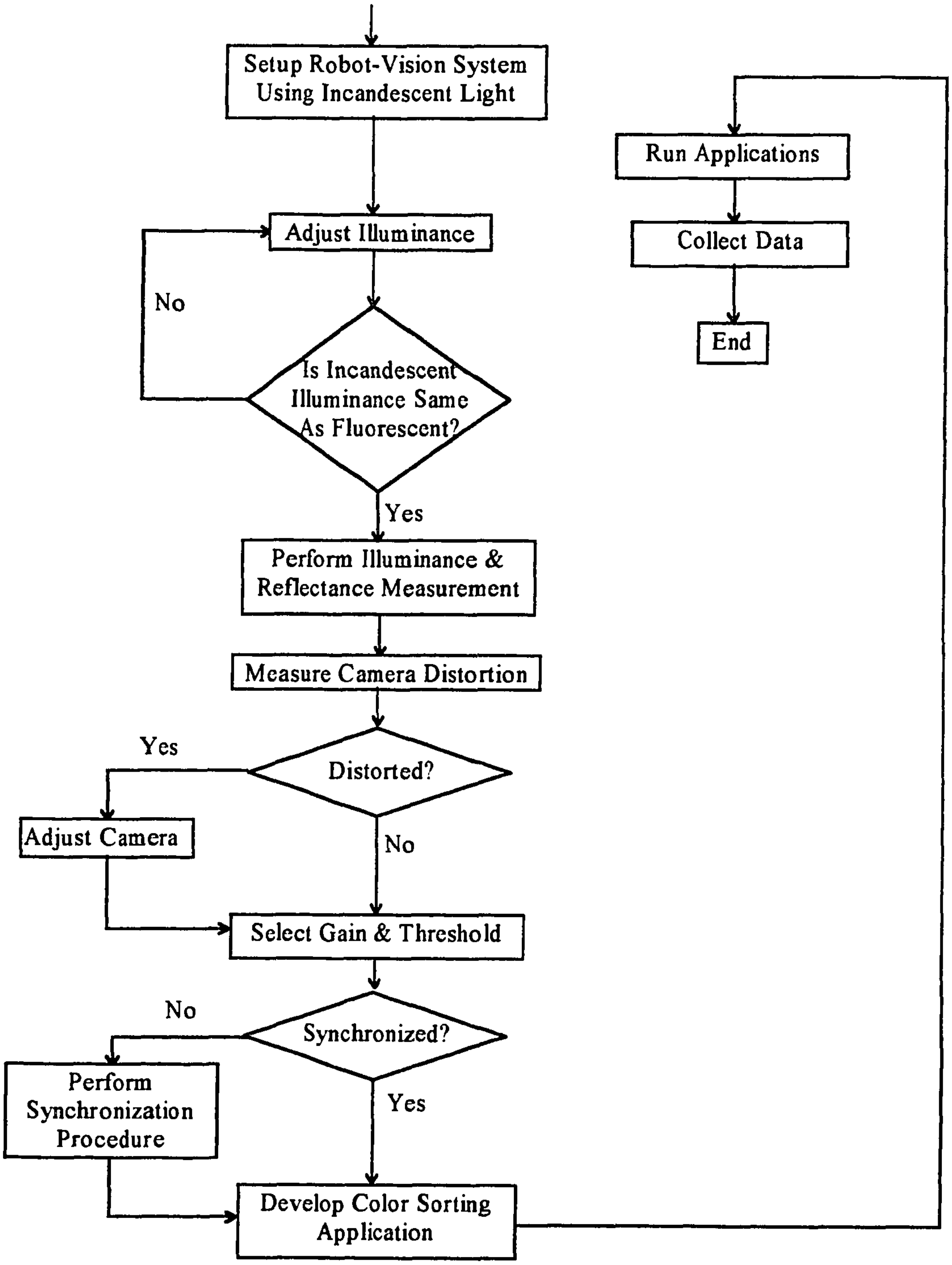


Figure 16. Flowchart of the procedures and steps taken to develop the sorting applications.

System Data

The characterizing of the robot vision system required a systematic approach to ensure the proper selection of the threshold values used in the sorting application. The data categories were synchronization, threshold grayvalues, and robot positions.

The synchronization data consisted of two robot point and vision point pairs and the conveyor synchronization speed. Each robot-vision point pair synchronized the robot with the vision system at a location in the camera's FOV. The two points taken together described the ranges of possible object location in the camera's FOV.

The robot positions depended on the robot vision material handling setup. These positions served to direct the robot to the various locations required by the material handling operation.

The variables used in determining the thresholds of the sorting application were light source, illumination and gain. Incandescent and fluorescent lamps were the two light sources selected. The illumination range of fluorescent lamps was 0-800 lux. The illumination range of incandescent lamps was 0-1300 lux. The gain range for the ROBOTVISIONplus system was 0-63, where 63 is minimum gain and 0 is the maximum gain. Samples of histogram peaks of the red and white dominos and the limit for the background were taken over the entire gain range and illumination range previously described.

Ten batches of data were taken at the illumination of 540 lux. This was the ambient lighting in the Robotics Lab where the experiment took place. Performance data were also taken at various illumination levels to determine the maximum and minimum operational illumination levels of the vision-based robot sorting system.

Analysis

For Questions 1-2, the gain with the largest difference in histogram peaks of the red and white domino was selected as the optimal sorting gain for that light source at 540 lux. The threshold value separating the two dominos was calculated by taking the difference in the low peak of the white domino and the high peak of the red domino divided by 2 and added to the high peak of the red dominos. For Questions 3-4, the percentages for the success and failure rate were tabulated for each of the light sources for 10 batches at the illuminance of 540 lux. For Question 5-6, one batch of data was taken from various illuminance ranging from (0 to 1300 lux for incandescent and 0 to 800 lux for fluorescent). The performances of the two light sources over the illuminance ranges were compared by examining the sorting percentages over the illumination ranges indicated.

Summary

The components, methods and procedures used in the development of the material handling system have been presented in this chapter. These components were the SCROBOT ER-V plus and conveyor, the ROBOTVISIONplus, two light sources, an incandescent light intensity controller, and 3 gravity feeders. The DX-200 illumination meter was used to measure illumination. The following procedures were presented: illuminance measurement, surface reflectance measurement, camera measurements, and robot to vision synchronization. The following methods were presented: threshold selection, Motor Mover control, color sorting (Method A and Method B), and illuminance control. The steps in the development of the application were discussed and a flowchart was constructed to facilitate application development. The dimensions and the characteristics of the dominos used were given and the type of expected data was indicated. Lastly, the procedures used to analyze the expected data were outlined.

CHAPTER IV

RESULTS AND DISCUSSION

During the course of this study, a vision-based robot material handling system was developed. Two methods of separating colors were implemented, but only one produced satisfactory results. Applications developed using Method A only worked in a limited illumination range and identification tolerances. Applications developed using Method B worked in a wide range of illuminations and were not dependent on identification tolerances. Method B was developed using the data collected on the camera's response. The plot of camera's response to varying illumination showed a "linear" and a "saturation" region. Based on this observation, threshold values were calculated for applications under incandescent and fluorescent lighting. Using these threshold values, the developed applications were able to sort colors in a wide illumination range under both incandescent and fluorescent lighting. The results were separated as follows: application development, system characterization data, and system performance data.

Application Development

Two approaches were taken in the development of the color sorting vision-based robot system. Only one produced satisfactory results for the application in a "factory" environment. The first approach, Method A, appeared to favor fluorescent lighting, because there were greater changes in object descriptors acquired than there were for incandescent lighting. However, after carefully controlling the illumination and adjusting the camera position, the developed sorting applications for both light sources were only working in a small range of identification tolerances and illuminations. Because of the difficulties associated with illumination control, the sorting applications generated using this approach could not be economically and reliably applied in the "factory" environment (varying AC line voltage, temperature, shadows, etc.). The second approach proved more promising. Sorting applications developed using Method B were successfully sorting over a large range of illumination under both the fluorescent and the incandescent lighting.

Because applications using Method A did not produce satisfactory results, the programs developed were not reported here. The results form the development of the sorting applications for the second approach are presented as follows: the Sorting Application Program (SAP), the robot coordinates used in the program, and the Sorting Performance Program (SPP).

The SAP performed the sorting of ten dominos: 5 red and 5 white. It directed the vision-based robot system to load, sort and unload the dominos automatically. The SAP also sent control signals to the Sorting Performance Program. The SPP analyzed the data acquired and generated a screen report. Figure 17 displays the flow chart of the SAP. The dominos were loaded into the conveyor in the order of 5 white dominos followed by 5 red dominos. This order was necessary for the SPP to collect data for evaluation purposes. However, the system could sort these dominos in any order.

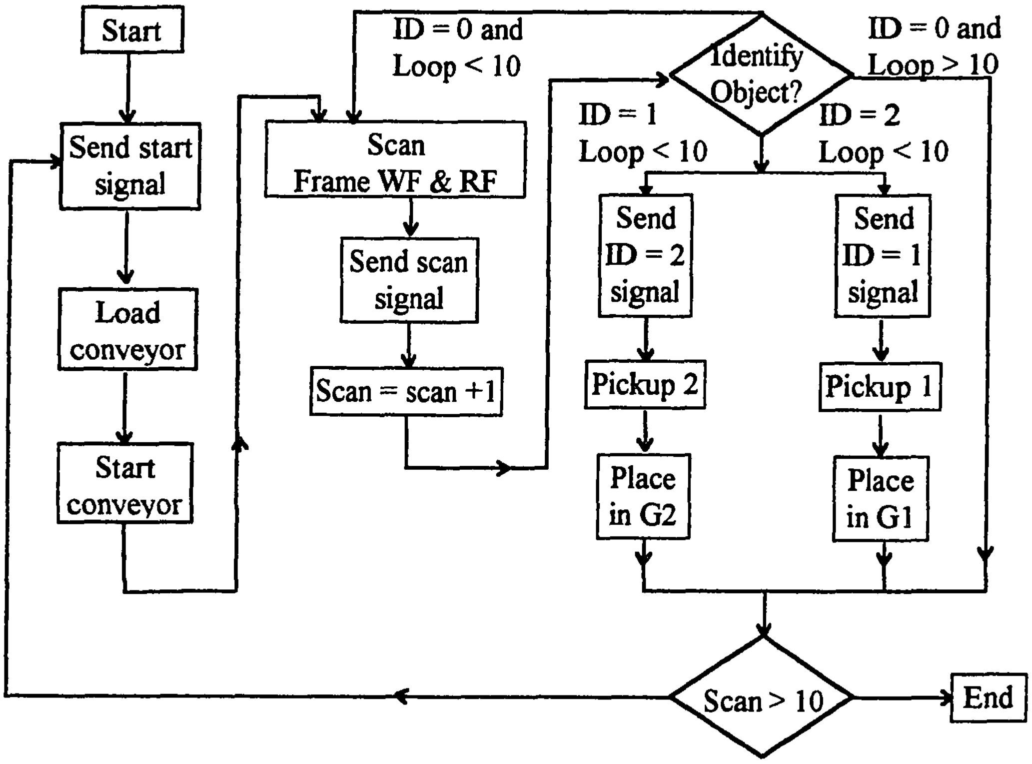


Figure 17. Flowchart of the Sorting Application Program.

Three frames were used to scan the conveyor belt surface (background) for the dominos. The ROBOTVISIONplus allowed applications to use 4 frames. One frame (WF) was used to separate the white domino from the background. One frame (RF) was used to separate the red domino from the background. Lastly, one frame (PF) was used to pick up the object from a moving conveyor. The size of the WF and RD frames was smaller than the size of the PF frame. The threshold value of the WF frame was determined by the differences in the histogram peaks of the red and white dominos. The threshold value for the RF and PF frames depended on the histogram high limit of the background. Although the RF frame was not necessary, it served as a position indicator for the red dominos. This helped the robot in picking up the red domino. It also helped to shorten the cycle time of the scanning, because scanning time for the small RF frame was shorter than the scanning time of the larger PF frame.

The robot was programmed to go to various locations during the execution of the sorting application (see Table 6). These locations were pre-set using the ROBOTVISONplus Teach Positions Menu. These positions were designed with the objective of generating the least amount of variation in the system. Table 6a presents the description of the robot positions listed, and Table 6b presents the actual robot coordinates used in the application.

The sorting data collecting program was developed using QBASIC. This program examined control outputs from the sorting program and determined the status of the sorting operation. It collected the Illuminace readings, also from the DX-200 through an A/D converter. This program can display and save the data collected to the monitor or to a file (see Figure 18).

System Characterization Data

The system data were measurements taken on variables that affected the performance of the material handling system. The data collected were categorized into light source illumination variations, surface and perimeter measurements of the red and white dominos, camera distortion measurements, threshold calculations, and histogram peaks and limit measurements.

Table 6

Coordinates for the Robot Positions Used in the Sorting Program. (a) Position descriptions. (b) Robot coordinates

(a) Position Description

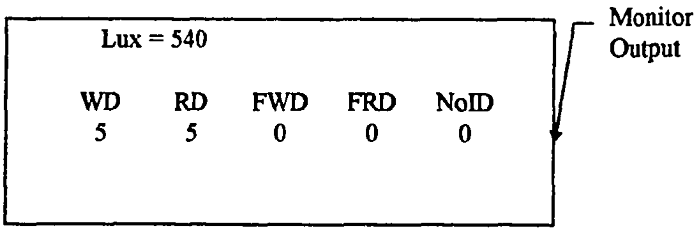
Position	Description
2	Ready
5	At G1
6	At G2
7	Above G2
8	Above G1
10	At G3
11	Above G3
12	Above conveyor
13	Down to conveyor
14	Above conveyor

(b) Robot Position

Position*	X (mm)	Y (mm)	Z (mm)	Pitch (degree)	Roll (degree)	Slidebase (mm)
2	128.4	217.0	149.5	-90	-63	0
5	18.7	350.3	87	-100	-87.6	0
6	41.8	402.8	88.5	-104.1	-87.7	0
7	49.1	348.5	145.8	-91.1	-88.5	0
8	168.4	326.4	130.2	-109.2	-88.7	0
10	580.4	-109.8	342.9	19	2.1	2260
11	549.9	-103.3	398.9	45.3	2.1	2260
12	531.3	101.8	38.6	51.0	-0.4	2260
13	408.9	117.8	48.6	-91.6	-42	2260

Note. Table 6a describes the locations of the robot positions with respect to other components in the vision-based robot material handling system. Table 6b contains the actual robot coordinate used in the ROBOTVISIONplus system.

* X, Y, Z, and slidebase positions are accurate to ±0.1 mm; Pitch and roll positions are accurate to ±0.1 degree.



The status of the sorting operation were reported in the following categories:

- WD: White domino correctly identified
- RD: Red domino correctly identified
- FWD: White domino incorrectly identified
- FRD: Red domino incorrectly identified
- NoID : Domino not identified

Figure 18. Sorting Performance Program display. The sorting performance program counts and tabulates the number of sorting successes and failures. In order to determine the status of the sorting action, the dominos must be placed in the order of 5 white domino followed by 5 red dominos. It then displays the data on the screen and saves them to disk.

Light Source Illumination Variations

Fluorescent and incandescent lamps produced different illumination variations. The fluorescent illumination appeared to be more stable than the incandescent when measurements were taken from the DX-200 Light Meter's LED panel and when 200 hundred measurements were averaged by the illumination measuring program. The A/D readings indicated differently. When using the A/D converter readings to take illumination readings, fluorescent readings shown an oscillation, while the incandescent did not.

Figure 19 shows the illumination versus time plot for both light sources during 2 separate eight-hour periods at night. Each illumination point was averaged over 200 A/D readings and converted into lux. Plots for the incandescent and fluorescent lighting had similar ranges (510-540 lux). However, the fluorescent illumination seemed to be affected more by the turning on and off of the lights in the next room. The initial rise in the illumination might have been caused by switching the lights off in the next room, while the drop off at the end might have been caused by the switching on of the lights in the next room. These changes in illumination coincided with the turning off and on of the lights when the researcher left at night and came back in the morning. The incandescent illumination had a larger variation than the fluorescent, but were not affected by the turning on and off lights in the next room. However, turning on and off of other equipment in the room also changed the illuminance of the incandescent lamps.

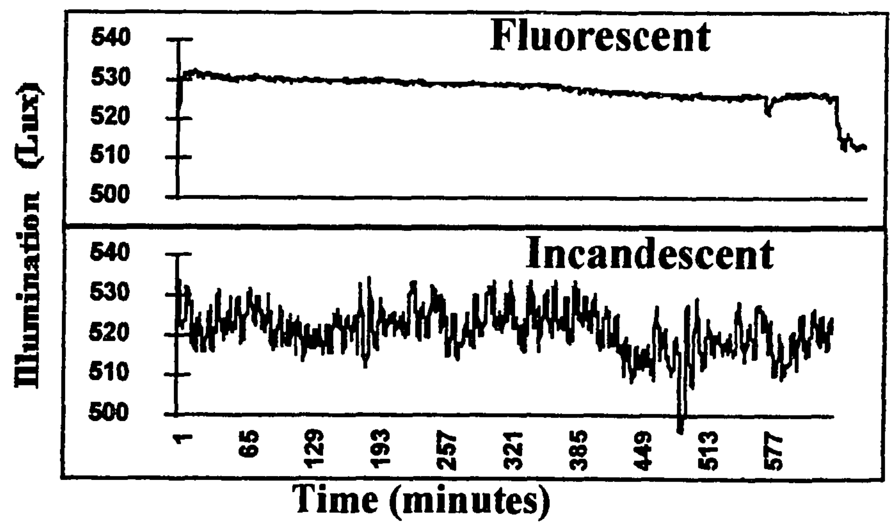


Figure 19. Fluorescent and incandescent illuminance vs. time.

Readings from the LCD display of the DX-200 light meter gave a misleading idea that fluorescent lighting is more stable, because the LCD illumination readings for the fluorescent appear stable, while the incandescent illumination readings tend to fluctuate. Figure 20 dispels this notion. As the figures shown, the incandescent illumination was stable in a 0.1 second period, while the fluorescent illumination varied. There were 12 peaks in the 0.1 second scan plot, which supported the theory that AC line voltage

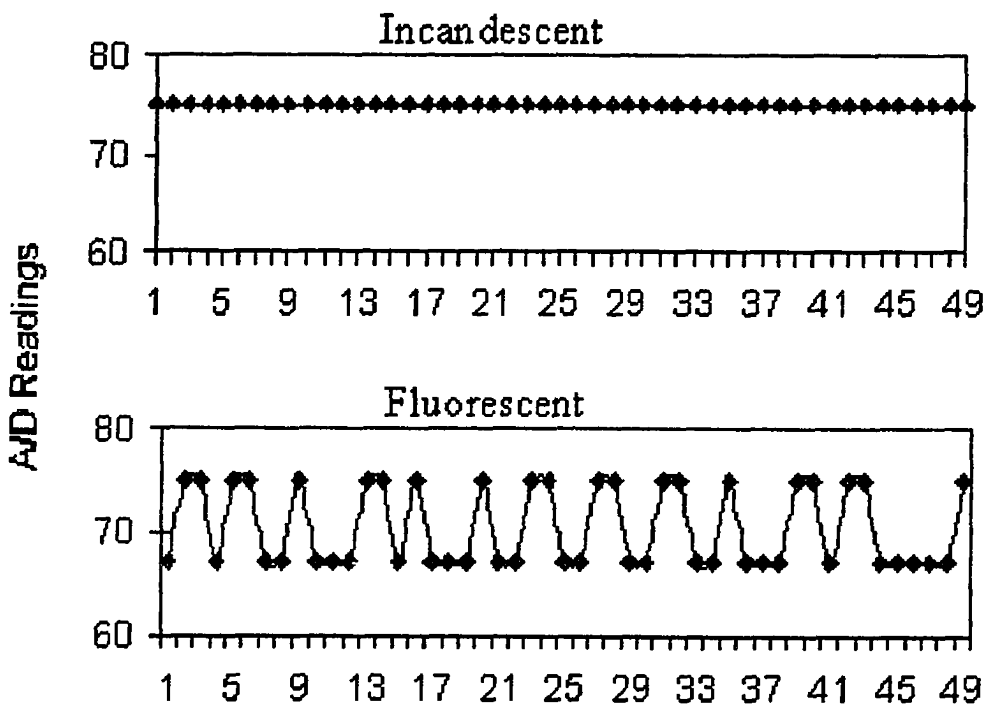


Figure 20. Fluorescent and incandescent illuminance A/D readings taken over a 0.1 second period at 540 lux.

caused a illuminance fluctuation. The 60 HZ AC voltage created 120 pulses of electric discharge (one for the positive and one for negative).

Both types of lamps had shown trends of decreasing illumination over time. The incandescent illuminance varied more than the fluorescent illuminance over a long period of time, but less over a short period of time. These significant variations in illumination for both light sources may explained why applications developed using the first approach, Method A, were not successful. Furthermore, these illumination variations demonstrated that, even in a period of relatively low power usage (night), the illumination will vary.

Surface Area and Perimeter Length Measurements

The surface area and perimeter length measurements of the dominos were an important indication of the effect of light sources. These object descriptors provided valuable data on the variability of the image processing portion of the vision system. Surface area was a two dimensional value, so its variability should be higher than the perimeter length (one dimensional). By taking data from stationary dominos, the variability of the values would only depend on the changes in the light source, gain, and threshold (see Tables 7 and 8). The samples were taken at illuminance ranges of 518-524 lux for fluorescent and 520-531 for incandescent lighting. The gain selected were 60, 55, 50, 45, 40. This gain range covered the effective range for the vision system, and as gain increased above 40 the background started to merge with the parts. The gain value at the point where the objects were indistinguishable form the background was different for each illumination level. The maximum histogram limit of the background was used as the threshold for each gain.

Table 7

Surface Area Measurements

	Average	Max.	Min.	Medium	Mode	STD	Variance
FRD 60-55	5593	5616	5576	5594	5596	8.934	79.82
FRD 55-67	5942	5952	5928	5940	5936	6.089	37.08
FRD 50-80	5945	5952	5936	5946	5948	4.619	21.33
FRD 45-98	5959	5976	5946	5960	5960	5.420	29.37
FRD 40-133	5946	5956	5940	5948	5948	4.426	19.59
FWD 60-55	6711	6720	6700	6712	6712	5.473	29.96
FWD 55-67	6721	6736	6708	6720	6720	5.507	30.33
FW 50-80	6726	6736	6716	6728	6728	4.152	17.24
FWD 45-98	6899	6916	6876	6900	6896	8.214	67.48
FWD 40-133	6725	6736	6716	6724	6720	4.897	23.98
IRD 60-59	6762	6772	6752	6760	6760	5.008	25.08
IRD 55-74	6752	6760	6744	6752	6752	4.621	21.35
IRD 50-85	6784	6796	6772	6784	6784	5.494	30.18
IRD 45-107	6777	6788	6764	6777	6776	6.061	36.73
IRD 40-142	6781	6792	6772	6780	6780	4.806	23.10
IWD 60-59	6926	6932	6924	6926	6924	2.504	6.271
IWD 55-74	6992	6928	6916	6924	6924	2.716	7.375
IWD 50-85	6931	6936	6924	6932	6932	2.386	5.609
IWD 45-107	6931	6936	6924	6932	6932	2.675	7.145
IWD 40-142	6930	6932	6924	6932	6932	2.486	6.179

Note. The surface area measurements consisted of 30 readings with the light sources indicated at the gain and threshold values indicated as followed: FRD = fluorescent red domino; FWD = fluorescent white domino; IRD = incandescent red domino; IWD = incandescent white domino. The numbers following the above codes stand for the gain and the threshold. The first number equaled the gain. The second number equaled the threshold.

Table 8

Perimeter Length Measurements

	Average	Max.	Min.	Medium	Mode	STD	Variance
FRD60-55	307	310	304	308	308	1.49	2.25
FRD55-67	312	314	310	311	310	1.72	2.95
FRD50-80	312	314	310	312	312	1.32	1.75
FRD45-98	314	316	312	314	314	.743	.552
FRD40-133	313	314	310	312	314	1.34	1.79
FWD60-55	333	336	332	332	332	1.14	1.31
FWD55-67	334	336	332	334	334	0.922	0.851
FW50-80	334	336	332	334	334	1.14	1.31
FWD45-98	338	340	334	338	340	2.10	4.40
FWD40-133	334	334	332	334	334	0.814	0.662
IRD60-59	333	336	332	332	332	1.26	1.59
IRD55-74	332	334	332	332	332	0.0507	0.257
IRD50-85	335	336	334	334	334	0.900	0.809
IRD45-107	334	336	332	334	334	1.14	1.31
IRD40-142	334	336	334	334	334	0.758	0.758
IWD60-59	332	332	332	332	332	0	0
IWD55-74	332	332	332	332	332	0	0
IW50-85	332	332	332	332	332	0	0
IWD45-107	332	332	332	332	332	0	0
IWD40-142	332	332	332	332	332	0	0

Note. The surface area measurements consisted of 30 readings with the light sources indicated at the gain and threshold values indicated as followed: FRD = fluorescent red domino; FWD = fluorescent white domino; IRD = incandescent red domino; IWD = incandescent white domino. The numbers following the above codes stand for the gain and the threshold. The first number equaled the gain. The second number equaled the threshold

The average surface area of the red domino was less than the average surface area of the white domino for fluorescent lighting. The average surface area of the red domino was less than the average surface area of white domino for incandescent lighting.

The largest difference in average surface area of the two color dominos was taken for the fluorescent lighting, while the smallest variance and standard deviation were taken for incandescent lighting.

The average perimeter length the red domino was less than the average perimeter length of the white domino for fluorescent lighting. The average perimeter length of the red domino was less than the average perimeter length of the white domino for incandescent lighting. The largest difference in average perimeter length of the two color dominos was taken for the fluorescent lighting. Vision measurements using incandescent lighting provided the smallest variance and standard deviation for perimeter length. The data also showed the perimeter length measurements for the white domino under incandescent lighting were constant and might be significant in inspection applications.

Table 9 contains the camera measurements using the method proscribed by the ROBOTVISIONplus manual. These measurements were taken before and after the

Table 9

Camera Measurements

Parameters	Measurement (in pixels)	
	Before	After
XWIDTH	50	50
YWIDTH	50	50

surface area and perimeter length measurements. These measurements indicated that the camera was not geometrically distorted.

Histogram peaks readings for the red and the white dominos and background histogram high limits were taken at a gain range from 63-36 using illumination around 540 lux. The histogram peaks readings for the red and the white dominos and the background histogram high limits were taken at a gain of 45 using varying illumination range from 0 to 1300 lux for incandescent and 0 to 800 lux for fluorescent lighting.

Figure 21 shown that high limits of the histogram for the background under incandescent lighting were at a higher level than the fluorescent at the gain range (63-36) used. The differences in the peaks of the red and the white dominos using fluorescent lighting were larger than the differences in the peaks of dominos using incandescent lighting. The plot of grayvalues versus gain for the red domino was not as straight as the plot for the white domino. There were differences in the red and white peaks for using both the fluorescent and the incandescent lighting, and the red histogram peaks for both light sources were above the histogram high limits of the background, so both light sources can be used in the sorting application.

Plots shown in Figure 22 reveal some interesting characteristics concerning the response of the CCD camera. The grayvalues of the acquired image would increase linearly with gain at a certain range of illuminance. This illuminance region was named the 'linear' region of the camera response. Once a certain illumination was reached, the grayvalue no longer changed with increases in illuminance. This illuminance region was

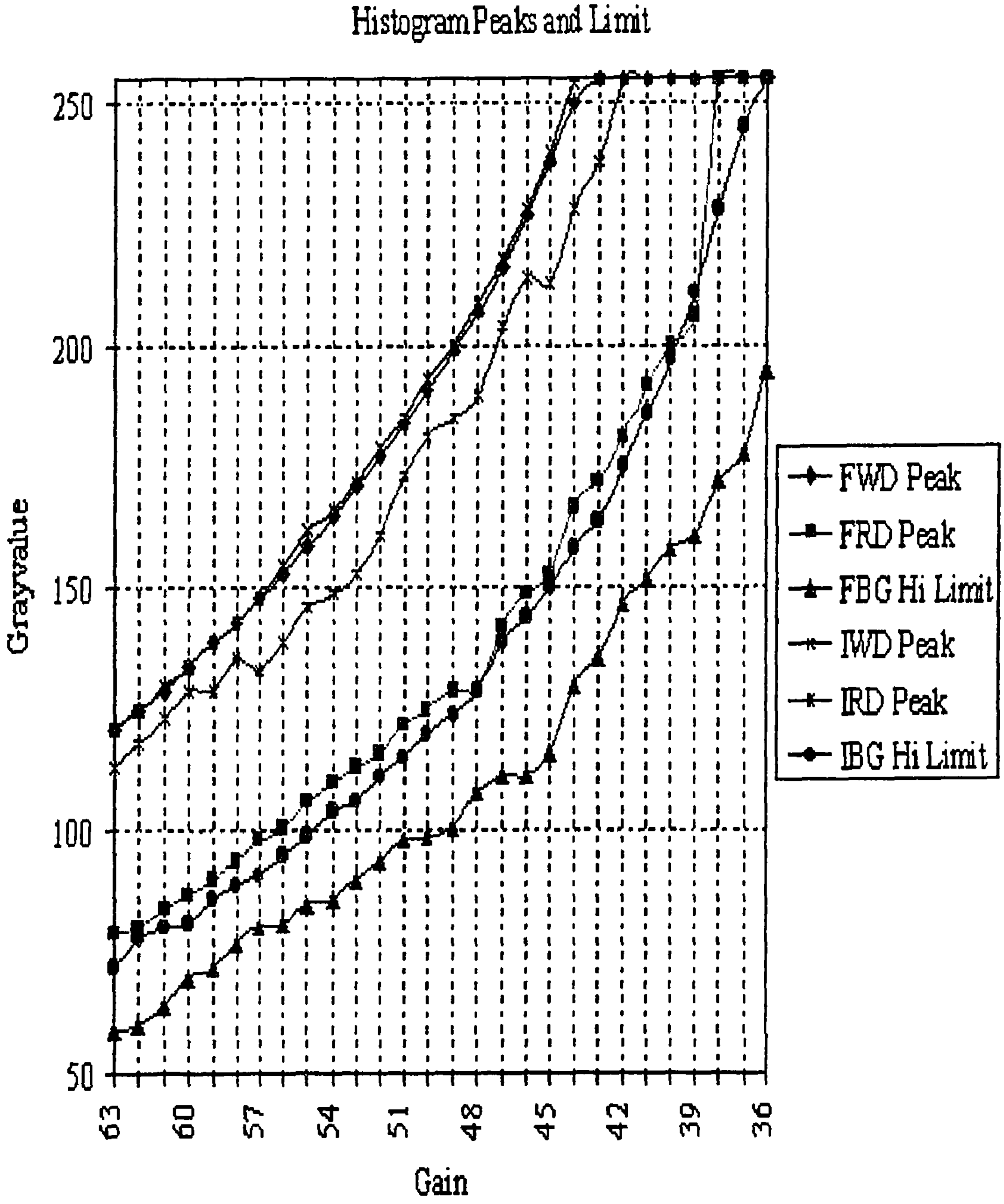


Figure 21. Histogram peaks and limits for red and white dominos at various gains at a constant illumination of 540 lux.

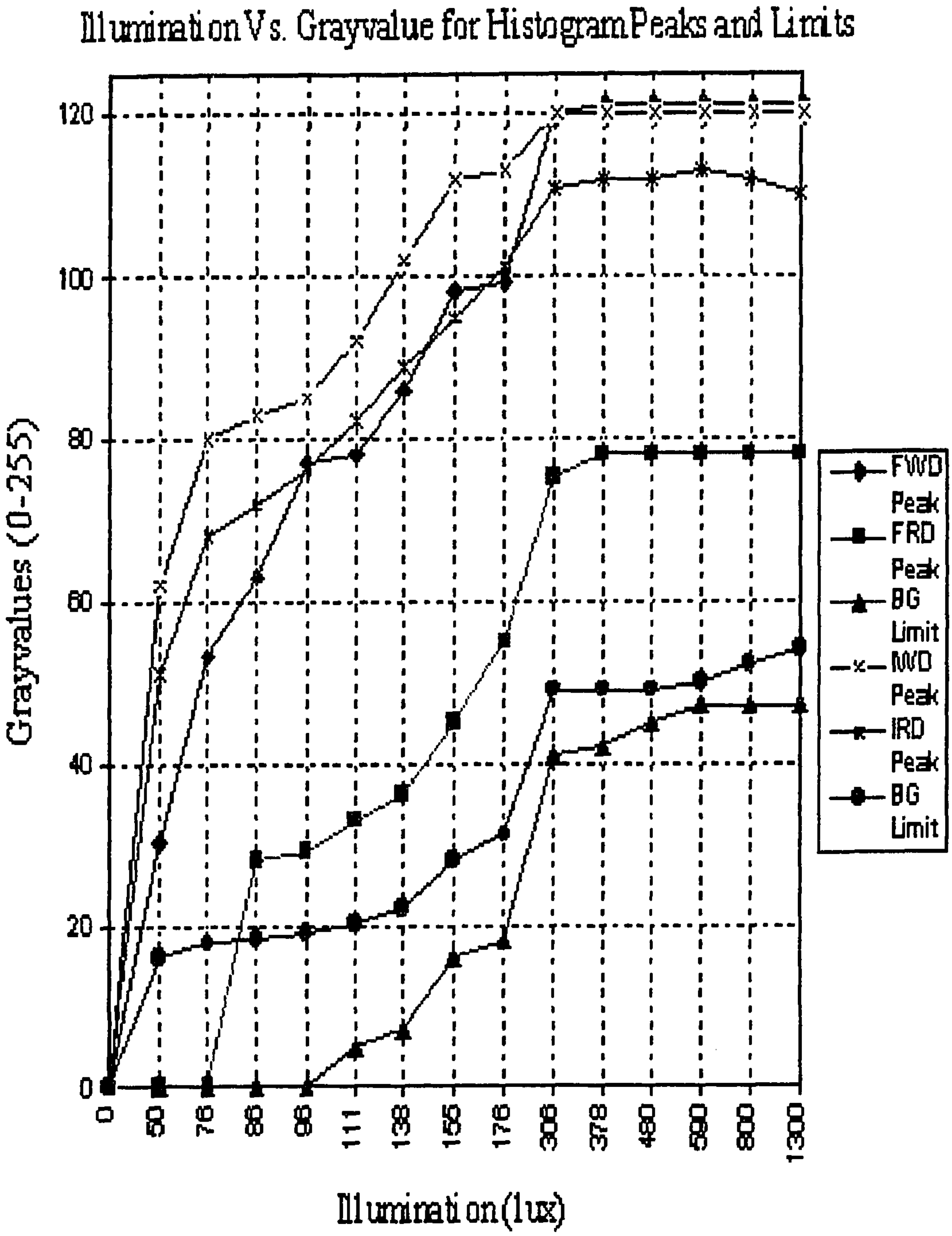


Figure 22. Histogram peaks and limits for red and white dominos at various gains at a constant illumination of 540 lux.

named the "saturation" region of the camera response. Although the camera response curve appeared very similar to the capacitor charging curve, there was no explanation for the fact that the CCD cell should have charged up according to the number of photons striking it and not according to the color or the reflectance of the parts. In theory the grayvalues should all reach the maximum grayvalue possible at that particular gain. The practical implication of the "saturation" region is that the vision sorting based on color or reflectance can operate within this wide "saturation" camera response region.

The measurements collected at illuminance of 540 lux and gain range of (63-36) were used to select the gain and the threshold levels used in the sorting application. The gain was selected to be the largest difference in the histogram peaks between the white and red dominos. The threshold used to separate the dominos was then calculated by dividing the peak difference by 2 and adding it to the histogram peak of the red domino. The threshold used to separate the dominos from the background was the high histogram limit of the background.

Table 10 contains the data used in the selection of the gain and the calculation of the threshold values. It was developed in Microsoft Excel. The difference of the peaks for the dominos was calculated by taking the difference between the peaks of the dominos. The maximum difference was determined using the MAX function in Excel. The threshold value was calculated as the maximum difference of the histogram peaks divided by 2 and added to the peak of the red domino. It is worth noting that as the gain increased above a certain point the difference became zero. If the difference was zero,

Table 10

Histogram Peak Values for Fluorescent and Incandescent Illuminance at 540 Lux

Gain	FWD Peak	FRD Peak	FBG Hi Limit	Diff. of Peaks	IWD Peak	IRD Peak	IBG Hi Limit	Diff. of Peaks
63	121	79	59	42	121	113	72	8
62	125	80	60	45	125	118	78	7
61	129	84	64	45	130	123	80	7
60	134	87	70	47	134	129	81	5
59	139	90	72	49	139	129	86	10
58	143	94	77	49	143	136	89	7
57	148	98	80	50	148	133	91	15
56	153	101	81	52	155	139	95	16
55	159	106	85	53	162	146	99	16
54	165	110	86	55	166	149	104	17
53	171	113	90	58	172	153	106	19
52	177	116	94	61	179	161	111	18
51	184	122	98	62	185	173	115	12
50	191	125	99	66	193	181	120	12
49	199	129	101	70	200	185	124	15
48	207	129	108	78	209	190	129	19
47	216	142	111	74	218	204	139	14
46	227	149	111	78	228	214	144	14
45	238	153	116	85*	240	213	150	27*
44	250	167	130	83	254	228	158	26
43	255	172	136	83	255	238	164	17
42	255	181	147	74	255	255	175	0
41	255	192	152	63	255	255	186	0
40	255	200	158	55	255	255	197	0
39	255	206	161	49	255	255	211	0
38	255	255	172	0	255	255	228	0
37	255	255	178	0	255	255	245	0
36	255	255	195	0	255	255	255	0

Note. The maximum difference for both the fluorescent and incandescent was at gain of 45. The threshold for fluorescent lighting was calculated as follows: (238 -153) / 2 = 195.5. The threshold for incandescent lighting was calculated as follows: (240 -213) / 2 = 226.5

* Maximum difference of peak value. They were selected using the MAX function in Microsoft Excel.

then sorting application would not be able to sort the two colors at that illuminance and gain.

System Performance Results

The performance data of the developed vision-based robot material handling system were separated into the performance data for applications developed using Method A and the performance data for applications developed using Method B.

Method A Performance Data

Sorting applications developed using Method A did not achieve an acceptable performance level. Under fluorescent lighting, the developed application was sorting reliably only in a limited identification range. The performance under the fluorescent lighting was achieving 100 % sorting success only for identification tolerances in the range of 0.35 to 0.45. The sorting applications developed using incandescent lighting were capable of better identification tolerances (0.2-0.3), but they were not able to sort reliably.

The sorting applications developed using Method A were very dependent on illumination. So, a small change in the illumination caused the developed application to fail in the sorting application. Increasing the illumination would cause the application to falsely identify red dominos as white ones. Decreasing the illuminance would cause the application to identify white dominos as red ones.

Detailed performance data collected using Method A were not reported here, because of the inability to obtain consistent results using the developed applications. For example, the application developed using Method A for incandescent lighting sorted perfectly at 0.03 tolerance one day (for 300 sorting operations), but were not able to identify any of the white domino on the following morning.

Method B Performance Data

A serie of performance data on the vision-based robot material handling system were collected on sorting applications developed using Method B. Sorting performances of these applications were not dependent on the identification tolerance. The data for the automated sorting and material handling operation were collected for the sorting of 5 red and 5 white dominos at various illuminations using the gain and thresholds identified and calculated in Table 10. Additional data were collected on the system's performance using illumination of 150 lux using fluorescent lighting. Threshold values for application at 689 lux were calculated based on the method outlined, but performance data were not collected, because these values were similar to the thresholds used for application at 540 lux. The illumination of 150 lux was chosen, because the recommended factory illumination level for the factory in packing application were between 150 and 300 lux. The illumination of 689 lux was chosen, because it was a convenient illumination above the 540 lux used in the developmental stage.

Tables 11 and 12 disply the performance data collected for both fluorescent and incandescent lighting at various illuminations. The illumination values for the fluorescent ranged from 95 lux to 760 lux. The illumination values for the incandescent ranges from 25 lux to 1500 lux. The data indicated that the system would not operate below a

Table 11

System Performance at Various Illuminations under Fluorescent Lighting

Illumination (lux)	WD	RD	False WD	False RD	NoID
760	5	5	0	0	0
675	5	5	0	0	0
540*	50	50	0	0	0
410	5	5	0	0	0
233	5	5	0	0	0
214	5	5	0	0	0
200	0	5	0	5	0
181	0	5	0	5	0
164	0	5	0	5	0
144	0	4	0	5	1
95	0	0	0	5	5

Note. WD = identification of the white domino; RD = identification of the red domino; False WD = identification of the red domino as the white domino; False RD = identification of the white domino as the red domino; NoID = no identification.

* Data collected during the initial development of the application using Method B.

certain illumination (100 lux for incandescent and 214 lux for fluorescent), but would operate successfully at higher illuminations. The data showed that the system could perform at a lower illumination with incandescent lighting then with fluorescent. However, they performed equally well above the cut off illuminance. The illuminance for the fluorescent lighting was not as easily controlled as the incandescent. So, the fluorescent illumination sample points were not as well spaced as the incandescent illumination sample points.

Table 12

System Performance at Various Illuminations under Incandescent Lighting

Illumination (lux)	WD	RD	False WD	False RD	NoID
1500	5	5	0	0	0
900	5	5	0	0	0
800	5	5	0	0	0
700	5	5	0	0	0
600	5	5	0	0	0
540*	50	50	0	0	0
500	5	5	0	0	0
400	5	5	0	0	0
350	5	5	0	0	0
300	5	5	0	0	0
250	5	5	0	0	0
200	5	5	0	0	0
150	5	5	0	0	0
100	3	5	0	2	0
50	0	5	0	5	0
30	0	0	0	5	5
25	0	0	0	0	10

Note. WD = identification of the white domino; RD = identification of the red domino; False WD = identification of the red domino as the white domino; False RD = identification of the white domino as the red domino; NoID = no identification.

* Data collected during the initial development of the application using Method B.

Table 13 contains the data and calculation used to determine the threshold values used to separate the dominos and the background. The dominos' histogram peaks and background's histogram limits were each collected 30 times. The threshold value for separating the white from the red domino was calculated by dividing the difference of the

Table 13

Histogram Peaks and Limit

Number	White Domino (grayvalue)	Red Domino (grayvalue)	Background (grayvalue)
1	176	95	71
2	176	95	62
3	176	84	63
4	176	95	62
5	175	98	63
6	176	98	62
7	176	95	62
8	176	95	59
9	176	98	63
10	176	95	63
11	176	84	62
12	175	95	63
13	176	95	64
14	175	95	64
15	176	95	61
16	175	84	66
17	175	99	64
18	175	95	59
19	175	95	66
20	176	102	60
21	175	97	62
22	176	102	61
23	175	101	64
24	176	95	60
25	176	98	67
26	175	106	60
27	175	102	61
28	175	104	65
29	175	102	66
30	176	104	64

Note. The histogram peaks and limit were taken at an illuminance of 150 lux and gain of 45.

minimum histogram peak of the white dominos and the maximum histogram peak of the red dominos by two and adding the maximum histogram peak of the red domino. The highest histogram limit of the background was selected as the threshold value that separates the background from the dominos. The low peak of the white dominos was at 175. The high peak of the red domino was at 106. The threshold value was calculated as follows: (175 - 106) / 2 + 106 = 104.5. It was rounded off to 105, because ROBOTVISION plus only took integer values for the threshold setting. The maximum histogram limit of the background was 71.

Table 14 contains the system performance data collected from the material handling operation using threshold values selected at 150 lux under fluorescent lighting. The system should have been able to sort the domino as long as there was a difference in the histogram peaks between the red and white dominos. In the "linear" region, a small change of illuminance could cause a large change in the histogram peaks of the dominos; so, the range of illumination where the sorting application could perform satisfactorily should be small. System performance data collected using the thresholds generated at 150 lux supports this prediction.

Table 15 contains the data used to select the threshold at 689 lux under fluorescent lighting. The low peak of the white domino was at 236. The high peak of the red dominos was at 153. The threshold was calculated as follows: (236 - 153)/2 + 153 = 196. This was the value calculated for the separation threshold value of the application at 540 lux. Background separation threshold was 117. This was also close

Table 14

Performance Data for Threshold Selected for at 150 Lux

Illumination	WD	RD	False WD	False RD	NoID
462*	0	0	0	0	0
350*	0	0	0	0	0
288*	0	0	0	0	0
266*	0	0	0	0	0
245	4	2	3	1	0
235	5	5	0	0	0
150	5	5	0	0	0
125	5	5	0	0	0
95	5	0	0	0	5

Note. WD = white domino; RD = red domino; False WD = identification of the red domino as the white domino; False RD identification of the white domino as the red domino; NoID = the system failed to identified any domino.

* The program execution were halted because the background were mixed with the object.

to the threshold of 116 for 540 lux. Due to the similar values of the thresholds, the performance data were collected. However this provided additional support for the prediction that above the saturation point for the illumination, the sorting application would run successfully.

Summary

The developed application worked within a large range of illuminations under both fluorescent and incandescent lighting, so it could be applied in a factory environment. The approach that used object descriptors did not work well in the separation of different colors. However, it could still work in a limited illumination

Table 15

Histogram Peaks and Limit

Number	White Domino (grayvalue)	Red Domino (grayvalue)	Background (grayvalue)
1	236	153	115
2	236	153	115
3	236	153	114
4	236	153	114
5	236	153	116
6	236	155	114
7	236	153	116
8	236	153	116
9	236	153	117
10	236	153	113
11	236	153	116
12	236	155	116
13	236	153	115
14	236	153	115
15	236	153	116
16	236	153	114
17	236	153	116
18	236	152	114
19	236	153	116
20	236	153	116
21	236	153	116
22	236	152	116
23	236	153	115
24	236	153	115
25	236	153	115
26	236	153	114
27	236	153	116
28	236	153	114
29	236	153	114
30	236	153	115

Note. The histogram peaks and limit were taken at an illuminance of 689 lux and gain of 45.

range. The application that used the difference in histogram peaks performed over a wide range of illuminations and could be used in an industrial environment of varying illumination. This approach would work as long as there is a difference in the histogram peaks of the objects being separated.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Summary

The development and implementation of an automated vision-based robot material handling system requires the systemic characterization of the entire system. By performing this characterization such a system is successfully developed. The developed system automatically sorts and monitors two parts with similar geometry under both the fluorescent and incandescent lamps over a wide illumination range.

The performance of the system depends on many variables. This study examines two independent variables: light source and color. The light sources not only differ in their spectral distributions, but also in their illumination variations, effects on the descriptors extracted by the vision system, and material handling system performance.

By examining these variables, an interesting phenomenon pertaining to the camera's grayvalue response to scene reflectance is observed. Using the "saturation" region of the camera response, a simple and effective threshold selection method is developed. The thresholds selected using this method enable the sorting program to sort dominos over a wide range of illuminations under each light source. This is very important for the application of this material handling system in the factory environment, because illumination variations exist for both light sources.

Conclusions

Several conclusions are drawn during the course of this study. They are as follows:

1. This automated material handling application works with both incandescent and fluorescent lighting.

2. Illumination of both the fluorescent and the incandescent lamps varies.

3. There is a “saturation” region for both light sources where the changes in illumination do not produce corresponding changes in the values of histogram peaks and limits.

4. There is a “linear” region for both light sources where the changes in illumination produce changes in the values of histogram peaks and limits.

5. The incandescent lighting produces a higher background histogram limit than the fluorescent lighting for this material handling system.

6. The fluorescent lighting produces a higher peak difference for white and red dominos than fluorescent lighting.

7. The incandescent lighting produces a smaller variance and standard deviation for the white domino than fluorescent lighting.

Recommendations

Based on the results this study, five recommendations may be drawn. They are as follows:

1. In the case of sorting applications where the two parts have different histogram peaks and are above the histogram limit of the background, using thresholds to separate colors is recommended over using object descriptors.

2. If energy consumption is not a major consideration, vision-based color sorting material handling applications should use illumination within the 'saturation region' of the illumination versus histogram curve.

3. If energy consumption is a major consideration and illumination is low, the illumination needs to be maintained at a constant level.

4. In the case of color sorting applications where the histogram limits of the background does not intersect with the histogram peaks of the parts, either light source can be used.

5. Applications that use object descriptors should consider the effects of light sources, color and surface reflectance on these descriptors.

Suggestions for Future Work

Based on the results of this study, the following suggesting for future work are drawn:

1. Further research is needed to uncover the physical laws that govern the camera's response to illumination, especially in the "saturation" region.

2. Further research is needed to develop applications which utilize the "saturation" region of the camera response.

3. This study should be replicated using different colors.

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APPENDIX A

CIE Chromaticity Diagram
and
Spectral Power Diagrams

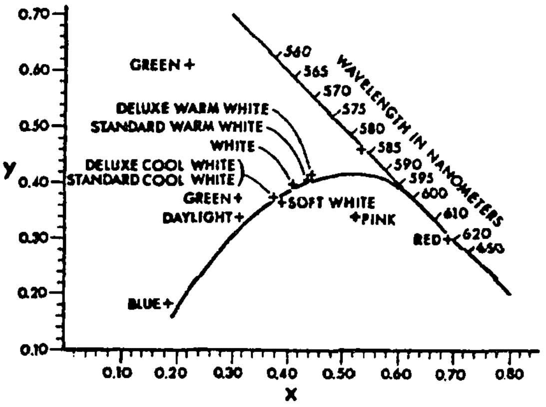
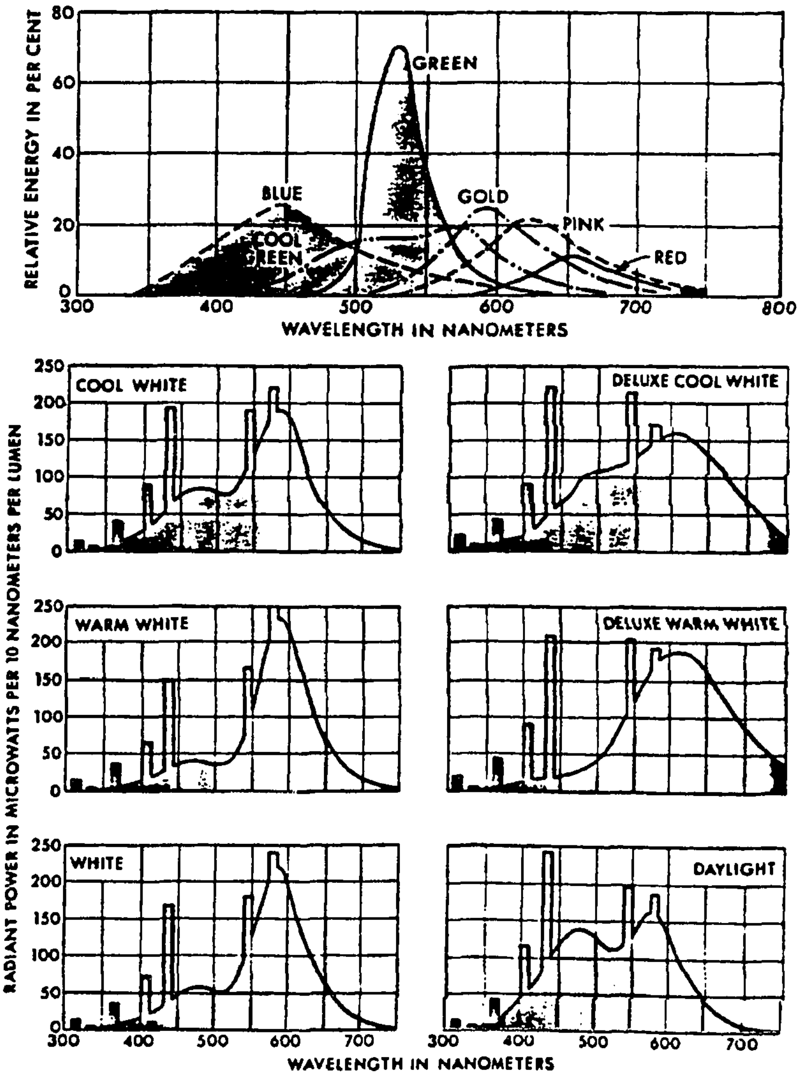
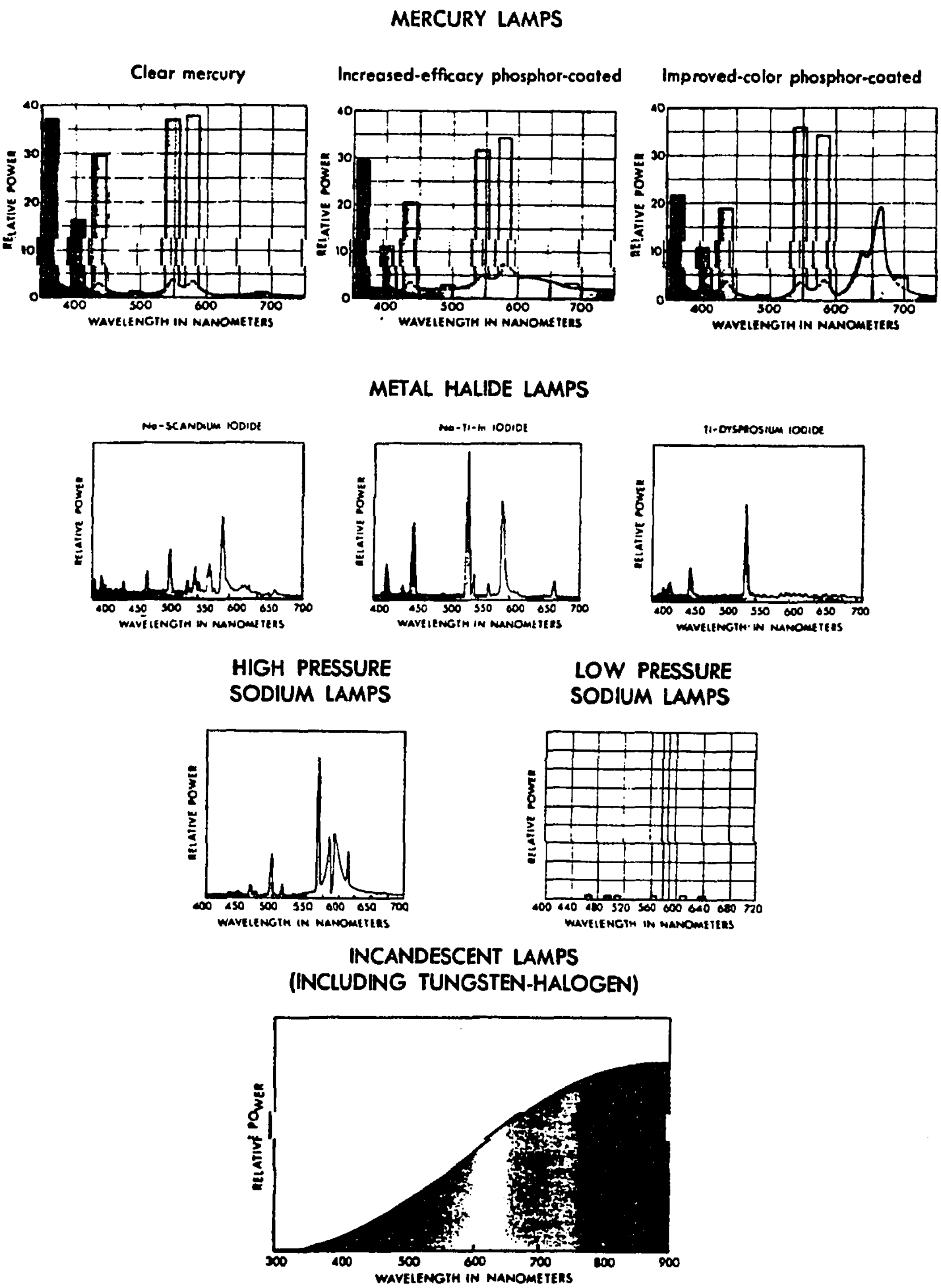


Fig. 8–23. (Left) CIE chromaticity diagram showing some white and colored fluorescent lamps in relation to the blackbody curve. (Below) Spectral power curves of light from typical fluorescent lamps. (Next page) Spectral power curves of high-intensity discharge and incandescent lamps (colors shown are approximate representations.) Consult Section 3 for details on the significance of these diagrams.



(figure continue)



Note. Source: Kaufman & Christensen, 1972, 8-19 to 8-20.

APPENDIX B

PROGRAM LISTINGS:

Sorting Application Program

Light Intensity Control Program

Illuminance Reading Program A

Illuminance Reading Program B

Sorting Performance Program

Sorting Application Program

```
1. SET VARIABLE WD TO 0        ‘ Initialize variables
2. SET VARIABLE RD TO 0
3. SET VARIABLE SC TO 0
4. OPEN GRIPPER
5. REMARK : MAIN PROGRAM EXECUTION LOOP
6. TURN ON OUTPUT #8        ‘ Send begin signal
7. TURN OFF OUTPUT #8
8. WAIT 50 10THS OF SECONDS
9. STOP CONVEYOR
10. GO POSITION 2 SPEED #3
11. IF VARIABLE SC = 10 JUMP TO 65
12. GO POSITION 11 SPEED #5        ‘ Load conveyor
13. GO POSITION 10 SPEED #5
14. CLOSE GRIPPER
15. GO POSITION 11 SPEED #5
16. GO POSITION 12 SPEED #5
17. GO POSITION 13 SPEED #5
18. OPEN GRIPPER
19. GO POSITION 14 SPEED #5
20. GO POSITION 2 SPEED #5
21. WAIT 50 10THS OF SECONDS
22. START CONVEYOR
23. SET VARIABLE CT TO 0        ‘ CT is used to limit the number of scans
24. OVERVIEW FRAME #1
25. IF VISUCESS JUMP TO 38
26. OVERVIEW FRAME #2
27. IF VISUCESS JUMP TO 52
28. SET VARIABLE CT = CT + 10
29. SET VARIABLE CT > 100 JUMP TO 31
30. JUMP TO LINE # 24
31. CALL SUBROUTINE #1
32. JUMP TO LINE # 5
33. SET SUBROUTINE # 1
34. SET VARIABLE SC = SC + 1
35. TURN ON OUTPUT # 7        ‘ Send scan signal
36. TURN OFF OUTPUT # 7
37. RETURN FROM SUBROUTINE
38. REMARK : SCAN AND PICK UP WHITE DOMINO
39. WAIT 10 10THS OF A SECONDS
40. SCAN AND PICK UP OBJECT # 0 IN FRAME #3
41. CALL SUBROUTINE #1
```

42. TURN ON OUTPUT #5
43. TURN OFF OUTPUT #5
44. STOP CONVEYOR
45. SET VARIABLE WD = WD + 1
46. REMARK : PUT WHITE DOMINO IN GRAVITY FEEDER #1
47. GO POSITION 8 SPEED #5
48. GO POSITION 5 SPEED #5
49. OPEN GRIPPER
50. GO POSITION 8 SPEED #5
51. JUMP TO LINE # 5
52. REMARK : SCAN AND PICK UP RED DOMINO
53. WAIT 10 10THS OF A SECONDS
54. SCAN AND PICK UP OBJECT # 0 IN FRAME #3
55. CALL SUBROUTINE # 1
56. TURN ON OUTPUT # 6
57. TURN OFF OUTPUT # 6
58. STOP CONVEYOR
59. SET VARIABLE WD = WD + 1
60. REMARK : PUT RED DOMINO IN GRAVITY FEEDER # 2
61. GO POSITION 7 SPEED #5
62. GO POSITION 6 SPEED #5
63. OPEN GRIPPER
64. GO POSITION 7 SPEED #5
65. JUMP TO LINE # 5
66. REMARK : DISPLAY VARIABLE VALUES
67. SET VARIABLE WD TO WS
68. SET VARIABLE RD TO RD
69. SET VARIABLE SC TO SC
70. SET VARIABLE SP = RD + WD
71. SET VARIABLE SP = SP * 100 ‘ Multiple by 100 to prevent division by zero error
72. SET VARIABLE SP = SP / SC ‘ Returns percentage of success

```
REM ********************************************************
REM LIGHT INTENSITY CONTROL PROGRAM
REM Author: Johnny T. Li
REM Spring 1996
REM University of Northern Iowa
REM
REM     This program controls the incandescent illuminance by reading the
REM signal output from the DX-200 and control the rotation of the stepper
REM motor using the Motor Mover
REM ********************************************************
DECLARE SUB readlight1 (outputdata#)
DECLARE SUB IncLight ()
DECLARE SUB DecLight ()
CLS:lightlevel = 0
DIM SHARED steps AS INTEGER
abspos = 0
   steps = 0
DO WHILE A$ <> "Q"
   readlight1 outputdata#
   lux = outputdata#
   LOCATE 10
   PRINT "LightLevel = "; lightlevel, "              "
   PRINT "Lux = "; outputdata#; "     "
   PRINT abspos
   illuminance = 520
   lightlevel = 0
   IF illuminance < lux - 5 THEN
      steps = -1
      DecLight
   END IF
   IF illuminance > lux + 5 THEN
      steps = 1
      IncLight
   END IF
   FOR i = 1 TO 10000: NEXT
LOOP
SUB DecLight
   OPEN "COM1:9600,N,8,1,RS,DS,CS" FOR RANDOM AS #1
    PRINT #1, "@STEP 1"; 0, 0, 0, 0, 0, -steps, 0
    INPUT #1, q
   CLOSE #1
END SUB
SUB IncLight
```

```
   OPEN "COM1:9600,N,8,1,RS,DS,CS" FOR RANDOM AS #1
    PRINT #1, "@STEP 1"; 0, 0, 0, 0, 0, -steps, 0
    INPUT #1, q
   CLOSE #1
END SUB


SUB readlight1 (outputdata#)
DIM lightreadings(1, 1000)
      outputdata# = 0:  intr = 1
      OUT &H3BC, 23: REM Send write pluse
      FOR i = 1 TO 1000: NEXT
      starttime = TIMER
      count = 0
      DO WHILE (TIMER - starttime) < 1
        count = count + 1
          OUT &H3BC, 23:  OUT &H3BC, 21: OUT &H3BC, 23
         intr = 1
          REM Read A/D conversion ready
          DO WHILE intr > 0
             intr = INP(&H3BE)
             intr = intr AND 8
             intr = intr XOR 8
          LOOP
         IF intr = 0 THEN
            OUT &H3BC, 22: lightreadings(0, count) = INP(&H3BD):
           lightreadings(1, count) = INP(&H3BE): OUT &H3BC, 23
          END IF
      LOOP
      FOR i = 1 TO count
          in3bd = lightreadings(0, i)
          in3be = lightreadings(1, i)
          in3bd7 = in3bd AND &H80
          IF in3bd7 > 0 THEN
           in3bd = in3bd AND &H7F
          ELSE
           in3bd = in3bd OR &H80
          END IF
          in3bd = (in3bd AND &HF8)
          IF (in3be AND 1) = 1 THEN
           in3be = in3be AND 6
          ELSE
           in3be = in3be OR 1
```

```
            END IF
            IF (in3be AND 2) = 2 THEN
             in3be = in3be AND 5
            ELSE
             in3be = in3be OR 2
            END IF
            in3be = (in3be AND 7)
            outputdata# = outputdata# + in3be + in3bd
        NEXT i
        OUT &H3BC, 0
        outputdata# = outputdata# / count
        PRINT outputdata#
        outputdata# = 515 / 115.5 * outputdata#: REM convert A/D input into lux
END SUB
```

```
REM *****************************************************************
REM Illuminance Reading Program A
REM Author: Johnny T. Li
REM Spring 1996
REM University of Northern Iowa
REM
REM   This program reads an 8 hour block (640 minutes) of illumination
REM from the DX-200 Illumination Meter The Signal output from the
REM DX-200 goes into a A/D converter which converts the analog signal
REM into digital signal. This program reads the digital signal from the
REM following parallel port addresses: &H3BC, &H3BD, and &H3BE.
REM   The inputted signal is averaged 200 times to approximate the signal
REM       output from the LCD display of the DX-200.
REM   The measured data is save into the file named by FileName$
'*****************************************************************
DIM lightreadingS(1001)
DIM lightave AS DOUBLE
DIM HourLux(640)
   minute = 0 :   samplesize = 0
   starttime& = TIMER
   PRINT starttime&
   DO WHILE minute < 640
   IF minute < INT((TIMER - starttime&) / 1) THEN
      minute = minute + 1
      samplesize = 0
      DO WHILE samplesize < 210
            samplesize = samplesize + 1
            intr = 1
            DO WHILE intr <> 1
               intr = INP(&H3BE)
               intr = intr AND 8
            LOOP
            intr = 0
            in3bd = in3bdorg
            in3be = In3beorg
            in3bd7 = in3bd AND &H80
            IF in3bd7 > 0 THEN
              in3bd = in3bd AND &H7F
            ELSE
              in3bd = in3bd OR &H80
            END IF
            in3bd = (in3bd AND &HF8)
            IF (in3be AND 1) = 1 THEN
```

```
          in3be = in3be AND 6
         ELSE
          in3be = in3be OR 1
         END IF
         IF (in3be AND 2) = 2 THEN
          in3be = in3be AND 5
         ELSE
          in3be = in3be OR 2
         END IF
         in3be = (in3be AND 7)
         REM PRINT in3be
         outputdata = in3be + in3bd
         IF intr = 0 THEN
          OUT &H3BC, 14
          In3beorg = INP(&H3BE)
          in3bdorg = INP(&H3BD)
          OUT &H3BC, 15
          OUT &H3BC, 13
          OUT &H3BC, 15
         END IF
         lightreadingS(samplesize - 1) = outputdata
         REM PRINT outputdata
       LOOP
     lightave = 0
     FOR i = 11 TO 210
      lightave = lightave + lightreadingS(i)
      IF hi < lightreadingS(i) THEN hi = lightreadingS(i)
     NEXT i
     lightave = lightave / 200
     PRINT "lightave"; lightave
     lux = 527 / 117.6 * lightave - 5
     HourLux(minute) = lux
     PRINT "minute"; minute, lux
   END IF
  LOOP
REM Save illuminance  readings in light.dat
     FileName$ = "Inc8hr.dat"
     OPEN FileName$ FOR OUTPUT AS #1
       WRITE #1, TIMER - starttime&
       FOR i = 1 TO 640
         WRITE #1, i, HourLux(i)
       NEXT i
     CLOSE #1
```

```
REM ********************************************************
REM  Illuminance Reading Program B
REM  Author: Johnny T. Li
REM  Spring 1996
REM  University of Northern Iowa
REM
REM  Data acquisition program for reading the illumination
REM  from the DX-200 Illumination Meter's signal output.
REM
REM  The Data is save into the file named by FileName$
REM
REM  The data is read from the parallel port addresses
REM    &H3BC, &H3BD, and &H3BE
REM
REM ********************************************************
DIM lightreadings(1, 50)
DIM lightave AS DOUBLE
DIM instantlux(50)
REM Get start time
starttime& = TIMER
PRINT starttime&
REM ************************************
REM Read 50 sample points (0.1 sec)
REM*************************************
FOR i = 1 TO 50
   intr = 1
   DO WHILE intr <> 1
      intr = INP(&H3BE)
      intr = intr AND 8
   LOOP
   intr = 0
   OUT &H3BC, 14
   lightreadings(0, i) = INP(&H3BE)
   lightreadings(0, i) = INP(&H3BD)
   OUT &H3BC, 15
   OUT &H3BC, 13
   OUT &H3BC, 15
NEXT i
endtime = TIMER - starttime&
REM ************************************
REM Convert readings to lux
REM*************************************
FOR i = 1 TO 50
```

```
    in3bd = lightreadings(0, i)
    in3be = lightreadings(1, i)
    in3bd7 = in3bd AND &H80
    IF in3bd7 > 0 THEN
     in3bd = in3bd AND &H7F
    ELSE
     in3bd = in3bd OR &H80
    END IF
    in3bd = (in3bd AND &HF8)
    IF (in3be AND 1) = 1 THEN
     in3be = in3be AND 6
    ELSE
     in3be = in3be OR 1
    END IF
    IF (in3be AND 2) = 2 THEN
     in3be = in3be AND 5
    ELSE
     in3be = in3be OR 2
    END IF
    in3be = (in3be AND 7)
    instantlux(i) = in3be + in3bd
NEXT i
REM ***************************************
REM Write data to file name FileName$
REM****************************************
FileName$ = "Inc.dat"
OPEN FileName$ FOR OUTPUT AS #1
   WRITE #1, TIMER - starttime&
   FOR i = 1 TO 100
      PRINT #1, i, instantlux(i)
      PRINT i, instantlux(i)
   NEXT i
CLOSE #1
PRINT endtime
```

```
REM : ***********************************************************
REM : Sorting Performance Determination Program
REM :
REM :    Author: Johnny Li
REM :    Spring 1996
REM :    University of Northern Iowa
REM :
REM :    This program takes the ROBOTVISIONplus ouput and summarize
REM :    the performance of the sorting operation. It also reads the
REM :    illumination during the sorting operation.
REM :
REM :    This program reads
REM :       ROBOTVISIONplus output through the Microbot Motor Mover
REM :       Illumination through A/D which converts the analog
REM :          from DX-200 Signal Ouput into digital signal
REM :
REM :    This Program Save the results in:
REM :       Var.dat : Single sorting operation
REM :       Sum.dat : Summarized result of 10 sorting operation
REM :
REM : ***********************************************************
DECLARE SUB readlight1 (outputdata#)
DECLARE SUB IncLight ()
DECLARE SUB DecLight ()
DECLARE SUB readlight (outputdata#)
DIM SHARED steps AS INTEGER
REM :*********************************************
REM : Open file
REM : Var.Dat = Single Sorting Operation
REM : Sum.Dat = Summary of 10 Sorting Operation
REM :*********************************************
OPEN "Var.dat" FOR OUTPUT AS #2
  PRINT #2, TIME$, DATE$
CLOSE #2
OPEN "Sum.dat" FOR OUTPUT AS #3
  PRINT #3, TIME$, DATE$
CLOSE #3
```

```
REM :******************************************
REM :  Open serial port channel to Motor Mover
REM :
REM :  h: input variable
REM :    33: scan
REM :     9: White Domino
REM :    17: Red Domino
REM :
REM :******************************************
OPEN "COM1:9600,N,8,1,RS,DS,CS" FOR RANDOM AS #1
CLS
FOR sample = 1 TO 30
   scan = 0
   NoID = 0
   FalseWD = 0
   FalseRD = 0
   WD = 0
   RD = 0
   DO WHILE scan < 10
      PRINT #1, "@READ"  REM :read input
      INPUT #1, a, b, c, d, e, f, g, h
      LOCATE 10, 1
      IF h = 33 THEN
         scan = scan + 1
         domino = 0
         FOR j = 1 TO 100
            h = 0
            PRINT #1, "@READ"  REM :read input
            INPUT #1, a, b, c, d, e, f, g, h
            IF h = 9 OR h = 17 THEN
               IF h = 9 THEN
                  domino = 1
                  WD = WD + 1
               ELSE
                  domino = 2
                  RD = RD + 1
               END IF
                     readlight outputdata#
               lux = outputdata#
               identity = domino
                     IF scan >= 6 THEN
                 IF domino = 1 THEN
                    identity = 3 REM :false identification of WD
```

```
          FalseWD = FalseWD + 1
        END IF
      ELSE
        IF domino = 2 THEN
          identity = 4 REM :false identification of RD
          FalseRD = FalseRD + 1
        END IF
      END IF
          IF identity = 0 THEN NoID = NoID + 1
      REM :*********************************************
      REM : Save illuminance  readings in file for
      REM :   items identified
      REM :  Codes for  the variable Identity
      REM :    0:not identified 1:white; 2:red; 3:falseWD; 4:False RD
      REM :********************************************
      OPEN "Var.dat" FOR APPEND AS #2
        PRINT #2, sample, scan, identity, lux
      CLOSE #2
    END IF
   NEXT j
   IF domino < 1 THEN
      REM :******************************************
      REM : Save illuminance  readings in file
      REM :   for items not identified
      REM :******************************************
      OPEN "Var.dat" FOR APPEND AS #2
        PRINT #2, sample; scan; 0; lux
      CLOSE #2
      domino = 0
   END IF
  END IF
  LOCATE 10, 1
  PRINT "h", "sample", "scan", "domino", "lux", " "
  PRINT sample; scan; domino, lux; WD, RD, FalseWD, FalseRD, NoID
 LOOP
 REM : ******************************************
 REM : Save summarized data into Sum.dat
 REM : ******************************************
 OPEN "Sum.dat" FOR APPEND AS #3
   PRINT #3, sample; scan; 0; lux; WD; RD; FalseWD; FalseRD
 CLOSE #3
NEXT sample
CLOSE #1
```

```
SUB readlight (outputdata#)
DIM lightreadings(1, 1000)
outputdata# = 0
intr = 1
REM : Send write pluse
OUT &H3BC, 15
count = 0
FOR i = 1 TO 200
        count = count + 1
          OUT &H3BC, 15
          OUT &H3BC, 13
          OUT &H3BC, 15
        intr = 0
          REM : Read A/D conversion ready
          DO WHILE intr = 0
               intr = INP(&H3BE)
               intr = intr AND 8
          LOOP
             OUT &H3BC, 14
           lightreadings(0, count) = INP(&H3BD)
          lightreadings(1, count) = INP(&H3BE)
          OUT &H3BC, 15
      NEXT i
      FOR i = 101 TO count
           in3bd = lightreadings(0, i)
           in3be = lightreadings(1, i)
          in3bd7 = in3bd AND &H80
           IF in3bd7 > 0 THEN
              in3bd = in3bd AND &H7F
           ELSE
            in3bd = in3bd OR &H80
           END IF
                 in3bd = (in3bd AND &HF8)
           IF (in3be AND 1) = 1 THEN
            in3be = in3be AND 6
           ELSE
            in3be = in3be OR 1
           END IF
              IF (in3be AND 2) = 2 THEN
            in3be = in3be AND 5
           ELSE
            in3be = in3be OR 2
           END IF
```

```
            in3be = (in3be AND 7)
        outputdata# = outputdata# + in3be + in3bd
        IF hi < in3be + in3bd THEN hi = in3be + in3bd
        IF lo > in3be + in3bd THEN lo = in3be + in3bd
    NEXT i
    OUT &H3BC, 0
    outputdata# = (outputdata# / (count - 100)) - 1.22
    PRINT outputdata#
       REM : convert A/D input into lux
    outputdata# = 527 / 115.5 * outputdata#
END SUB
```