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The Development of the Landmark Tracking System

Eun Ho Lee

Engineering Research Center for Advanced Control and Instrumentation (of SNU)
by Korea Science and Engineering Foundation(KOSEF)
Seoul, Korea

Steve Dickerson

The George W. Woodruff School of Mechanical Engineering
Georgia Insitute of Technology
Atlanta, GA, U.S.A.

ABSTRACT

A landmark tracking system (LTS) has been developed for use in locating objects in a manufacturing environment. The Landmark Tracking System is an integrated system which consists of a grey scale CCD camera, an image processor, an illumination system based on electronic flash, and software intended primarily for tracking retroreflective landmarks. The term "integrated" means that the camera electronics and the strobe electronics are directly linked to the computer system, governed by the same clock and under direct software control. A novel element in the LTS is that a pinhole is used for the optics.

1. Introduction

In manufacturing environments, there are many situations in which position measurement is required. Many systems rely on indirect methods to get position data, such as measuring the joint angles of a robot manipulator, or counting the number of pulses from a lead screw encoder in a machine tool. However, these methods cannot provide the actual position data of the object in many cases, because of the effects from deflections or vibrations. This problem becomes more critical as manufacturing systems get faster and more accurate, and this can be solved by direct measurement. Convenient direct measurement usually requires non-contact. This can be achieved in several ways, such as using vision, ultrasonics, lasers, radar, and so on. Among the possible choices, a vision method is considered to be the most favorable as it offers fairly good performance at low cost and compact size. There have been many works about visual measurement system, and several attempts which reduce the computational load while increasing accuracy and reliability have been made by employing special marks or fiduciaries with known geometry which are attached at a predetermined location[1,2,3].

The Landmark Tracking System[4,5,6] measures the position of special targets which are much brighter than other objects in manufacturing environments. The brightness is achieved by employing retroreflective material and the illumination from an integrated strobe unit, which is a part of the camera head. The LTS is a totally self-contained system which consists of a grey scale camera, a control and processing computer, a strobe unit, and software intended primarily for tracking retroreflective landmarks. Because the landmarks are of known geometry, and also because they are very bright if properly illuminated, the processing speed as fast as 100 per second has been achieved. After the processing, the position data can be fed into the host computer via a serial interface of the LTS.

Understanding the characteristics of retroreflector, optics, and illumination is important in this research. The LTS obtains the position of landmarks using the image intensity distribution on the sensor surface, and all three factors above can influence it. This paper deals with the optical part of the LTS design; illumination, optics, and retroreflectors. Analysis on each subject has been made, and their relationships on the system performance are investigated. Finally, experimental data with a prototype of the LTS is presented with respect to repeatability and accuracy of the landmark position measurement.

2. Retroreflective Landmark

The LTS requires an image in which the landmarks are distinct from other objects. The landmark(or fiduciary) is assumed to be of known geometry, and is placed at a predetermined location. The resulting image permits rather simple image processing algorithm for calculating the landmark's position, while keeping accuracy and reliability. The landmarks should be much brighter than other objects in a field of view. Small light bulbs or LED's may do that job, but the power requirements for those landmarks are obstacles to system flexibility, which is one of the research objectives. For this reason, retroreflective material is chosen to be the landmark material.

There are three basic modes of reflections: specular reflection, diffuse reflection, and retroreflection(see Fig.1). Retroreflection is different from the other two common reflections because the reflected beam travels back in the direction of the incident light beam[7,8,9]. Retroreflection generally does not occur naturally. Thus we do not Hxpect to have unintentional landmarks in a field of view. A typical example of a retroreflector is a corner cube, which are easily found in a reflector on bicycles. Most retroreflectors in traffic control applications are made out of small glass beads(5 - 50μm dia.) with mirror coating on their back hemisphere(see Fig.2). They are usually pressed into a sheet to make sheet type retroreflectors, or mixed with paint to make retroreflective surfaces. In this research, sheet type retroreflector from 3M(Scotchlite) is used as landmark material because it offers flexibility in putting the landmarks on any position.

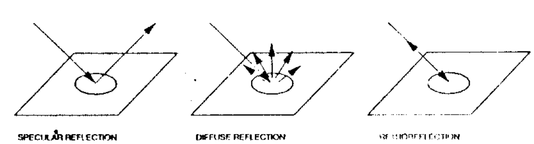

Fig.1.Types of Reflections

The optical characteristics of retroreflective material, especially when it is in sheet form, is usually represented by R', the Coefficient of Retroreflection[8].

$$R' = I/E_{\perp}A \tag{1}$$

where I = intensity of reflected light from the retroreflector in the direction of observation.(Watts/sr or candela(=lm/sr))

$E_{\perp}$ = illuminance at the retroreflector on a plane perpendicular to the direction of the incident light.(Watts/m^2 or lux(lm/m^2))

A = retroreflecting surface area.(m^2)

The coefficient of retroreflection, R', is expressed by vendors in candelas per lux per square meter($cd \cdot lx^{-1} \cdot m^{-2}$). R' decreases very rapidly as the observation angle(see Fig.3) grows bigger. Usually, it decreases by more than 50 % if the observation angle is greater than 1 degree. On the other hand, R' does not decrease fast as the entrance angle grows. R' usually retains 70 % of its peak value with +- 20 degrees of entrance angle[7,8]. In Fig.4. is the experimental R' data supplied by the 3M company, on Scotchlite #3870 White, with respect to observation angle and entrance angle.

The optical characteristics of glass bead type retroreflectors can also be obtained analytically using geometric optics. Using the definition of the coefficient of retroreflection and energy continuity equation, the R' of a glass bead retroreflector can be obtained. Results of this analytic method are given in Fig.5, where R' is plotted with respect to observation angle. The graph is very similar to that of Fig.4, and the differences come from the imperfectness of real retroreflectors. It is found that R' is heavily influenced by the refractive index of the glass bead. The theoretical maximum value of R' is obtained when the refractive index is 2.0, but because of the imperfectness involved in manufacturing retroreflectors, the refractive index which is slightly smaller than 2.0 is preferable. This is verified by the experimental data from 3M[10], which states that the optimum value lies between 1.7 and 1.9.

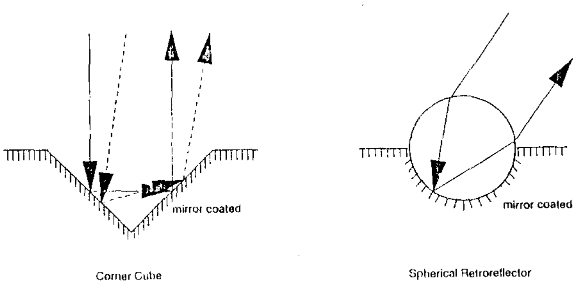

Fig.2. Types of Retroreflectors

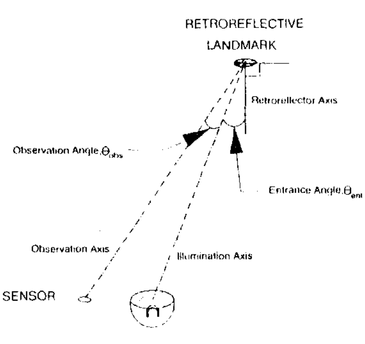

Fig.3. Optical Elements in Retroreflection Analysis

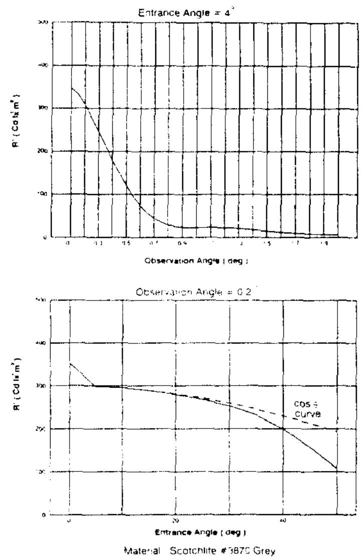

Fig.4. R' Data for Scotchlite #3870

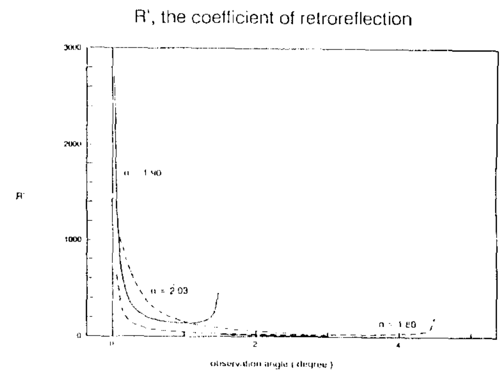

Fig.5. R' Data Obtained Analytically

3. Pinhole Optics

The requirements for the LTS optics are:

1. A high f/STOP so that all objects but the retroreflective landmarks remains very dark. This lightens the computing load, which is one of the LTS research goal.
2. Light-weight and compact.
3. A large depth of field.
4. Low cost.
5. Maximum utilization of retroreflective characteristics.

Considering these requirements, a pinhole is chosen as the LTS optics. Pinhole cameras have seen several applications in industry [11,12]. In addition to the above advantages, pinhole optics does not have the distortion effects usually found in lens based optics[13]. Since the beginning of pinhole camera, many works have been done to determine the pinhole size, as the image quality is related to it[14,15,16,17]The optimal size of pinhole is obtained based on a criterion that the most light energy from a point light source should land in the smallest image diameter. The image from a point source is explained using Fresnel diffraction equation, and the image diameter is expressed as a function of light wavelength and focal distance. As in Fig.6, the minimum image diameter is obtained when $r^2 = 1.4/2 * f\lambda$, which is obtained using numerical methods. This gives that the optimal diameter of the pinhole is given as

$$d = 1.67\sqrt{f\lambda} \qquad (2)$$

where d : pinhole diameter
f : focal distance
λ : wavelength of the light

However, larger pinhole size which was suggested by Lord Rayleigh[15] was used in the experiments, which is given as $d = 2 * \sqrt{f\lambda}$, to get brighter images, while slightly sacrificing image qualities. The optics system used in the experiments has a pinhole diameter of 100 μm. It has a 32 degrees field of view (FOV), and the resulting f/STOP is f/45.

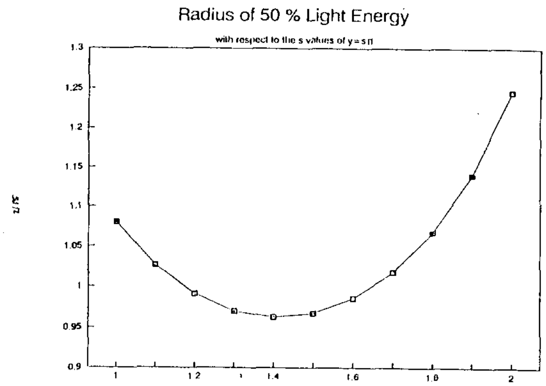

Fig.6. Optimal Pinhole Size

4. Illumination

The nature of retroreflection determines the illumination system of the LTS. The light source should be as close as possible to the optical axis to get the maximum response. Nearly coaxial illumination is necessary especially when the landmarks are at close range. Fig.7 shows a few possible designs for LTS illumination. If the landmark distance is much greater than the optical axis-light source distance, the observation angle will always remain smaller than 1 degree, so coaxial illumination is not necessary.

As the LTS is a dynamic position measurement system, its lighting system must provide very short, intense illumination. This will enable the system to freeze the motion of the landmarks, so to minimize any blurring. For a high S/N ratio, the illumination should be of a strength so that the peak intensity of a tracked landmark will be near the saturation limit of the detector. Finally, the illumination system should not be expensive.

The light sources that could be considered include an electronic flash, LED, and laser. Considering all factors, especially in terms of short, intense light, electronic strobe flash was chosen. It achieves short, intense light by discharging the electric energy stored in a capacitor through a tube filled with gas (usually Xenon)[18]. The period of light is usually less than 1 msec.

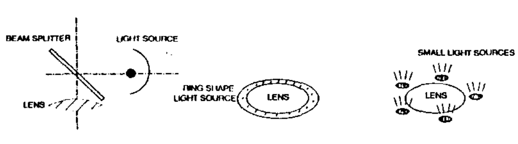

Fig.7. Illumination Designs for the LTS

5. Analysis on Error Sources

As previously stated, one of the advantages of the pinhole optics is it is without geometric distortion. However, errors in calculated landmark azimuth and elevation can arise from other sources. One factor that can be considered is the error caused by non-uniform irradiance. The cosine fourth law[19] shows that even for a retroreflector of uniform properties and for an ideal illumination, the intensity of the landmark image on the CCD detector will decrease as the landmark moves away from the optical axis. As a result, the light intensity distribution over a round landmark image area will not be symmetric. Because the moment method[20] is used to estimate the position of the landmark, there may be some shift of the estimated landmark position toward the optical center, especially when the landmark is large. This is illustrated in Fig.8. This inward shift will result in nonlinear radial distortion. The distortion will be small if the landmark size remains small. Simulation analysis has been done to investigate this effect. Its result is in Fig.9. In this simulation, the landmark image is assumed to have a radius of 45μm, and it corresponds to an area of 28 pixels of the CCD detector used in this research. Then the maximum distortion is 0.11 μm, which is approximately 1 part in 10000 of a field of view.

The other possible source of error is the pinhole thickness. Unlike an ideal pinhole with zero thickness, actual pinhole has thickness which is sometimes comparable to its diameter. If a thick pinhole is viewed from an oblique angle, its effective area will look smaller than the real one, and this results in a change in image intensity distribution. This is investigated using a similar method to study vignetting effect, and the results are given in Fig.10. It also shows that this effect remains small if the landmark size is small, which again justifies the use of small landmarks.

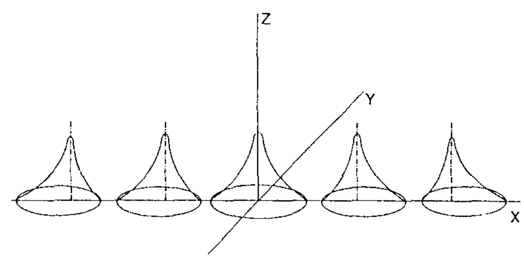

Fig.8. Image Intensity Shift

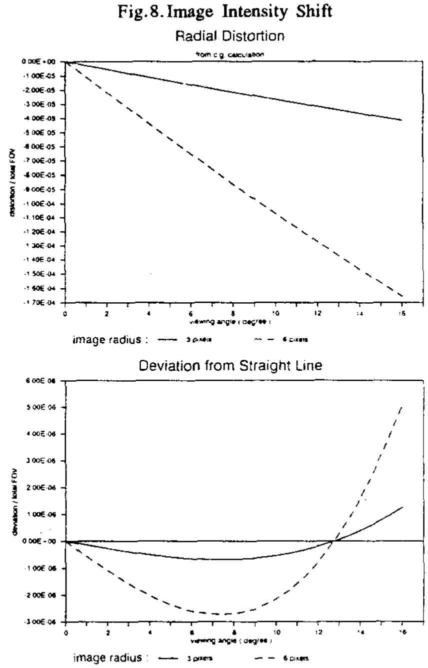

Fig.9. Distortion due to Image Intensity Shift

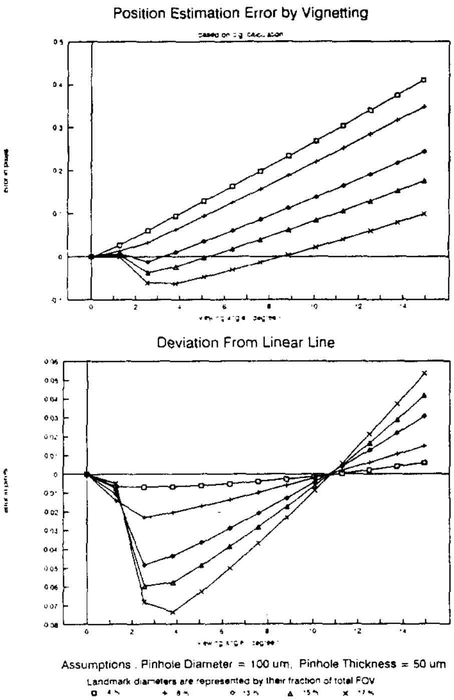

Fig.10.Distortion due to Pinhole Thickness

6. Experiments

The performance of the landmark tracking is measured in two ways, one is the repeatability of the landmark position estimation, and the other is the accuracy of the measurement. These experiments are performed with a prototype of the LTS.

A fixed circular retroreflective landmark and the fixed LTS camera is used to measure the repeatability of the landmark position measurement. 100 hundred pictures are taken, and its results are recorded for later comparison. Several experiments with different landmark sizes and distances show the repeatability of the landmark position calculation to be excellent. An example is shown in Fig.11.The landmark is .50"diameter circle, and the target distance is 20 inches. The landmark position calculation result is plotted both in row and column directions. They show very small standard deviation values, which are less than 5/1000 of a pixel. Because there are well over 150 pixels in each direction, row and column, the standard deviation of the position measurement repeatability is 1/30,000 of the field of view.

The accuracy of the landmark position estimation is measured next. For this experiment, a linear row of .250"diameter retroreflective landmarks is attached on a precision X-Y table. The X-Y table is placed at 2 feet from the LTS camera. In the landmark row, retroreflectors are spaced 1 inch apart. The X-Y table is programmed to move in increments in the Y direction. The resulting array of landmarks is pictured with the LTS and the landmark positions are calculated for each exposure. The output of this experiment is in Fig.12.Because pinhole optics do not have optical distortions but could have very minor distortions of the type suggested earlier, linear lines in the object space should remain linear in the sensor surface. The landmark image sizes are in the range of 21 to 35 pixels, which generates a very little distortion due to asymmetric intensity distribution. Thus the points on Fig.12. should form straight lines. Linear regression analysis has been done for these points. The RMS error of the deviations from straight lines are less than 1/20 of a pixel. This corresponds to 1/3,000 of a total field of view.The other method to measure the accuracy is the camera calibration method. In this experiment, camera calibration based on Tsai's method[21] is used. In addition to accuracy, this method also generates other system parameters, such as effective focal length, image center position, and distortion parameters. The results from this method also shows that this system has a 1/3,000 accuracy.

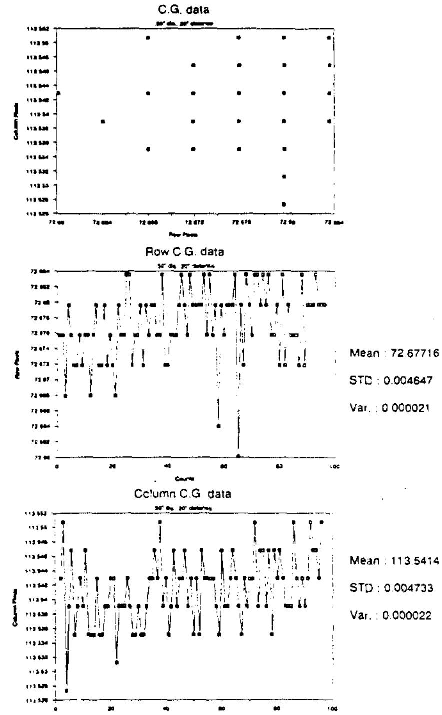

Fig.11.Repeatability Test Results

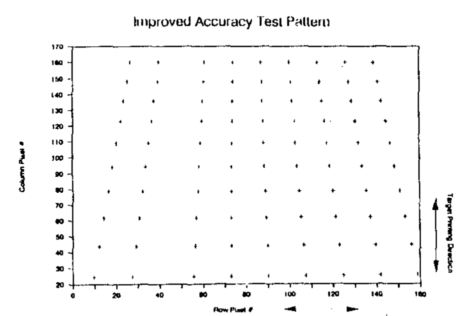

Fig.12.Test Pattern for Accuracy Measurement

7. Conclusion

In this paper, the Landmark Tracking System, which is a non-contact position measurement system is described. The LTS is a totally integrated system which combines a grey scale camera, processor, illumination unit, and a software to drive it. This paper deals with the analytic methods to investigate the optical elements in the LTS. Retroreflective landmarks are used in the LTS because it offers flexible methods to achieve bright targets. Retroreflector's optical characteristics are introduced, and it is analytically derived using geometric optics. It is found that the optical characteristics of glass bead retroreflector is closely related to the refractive index of glass bead, and the optimum value is slightly less than 2.0.Pinhole optics is used in the LTS, and the optimum pinhole size is obtained numerically from a Fresnel diffraction equation.

Analysis is done about the possible distortion in landmark position estimation due to illumination non-symmetry, and pinhole thickness. It is found that both effects are small enough until the landmark size remains small, which justifies the use of small landmarks.

Experiments are performed to measure the performance of the landmark tracking, in terms of repeatability and accuracy. The repeatability is better than 1/30,000 of a field of view. The accuracy, which is confirmed by camera calibration, is better than 1/3,000 of a field of view. Future research will deal with such issues as the influence of landmark size on the system performance, and algorithms to correct variations in pixel sensitivity.

8. References

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