

Optics, Illumination, and Image Sensing for Machine Vision V

Donald J. Svetkoff
Kevin G. Harding
Gordon T. Uber
Norman Wittels
Chairs/Editors

8–9 November 1990
Boston, Massachusetts

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Volume 1385

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Please use the following format to cite material from this book:

Author(s), "Title of Paper," *Optics, Illumination, and Image Sensing for Machine Vision V*, Donald J. Svetkoff, Editor, Proc. SPIE 1385, page numbers (1991).

Library of Congress Catalog Card No. 90-64018
ISBN 0-8194-0452-7

Published by
SPIE—The International Society for Optical Engineering
P.O. Box 10, Bellingham, Washington 98227-0010 USA
Telephone 206/676-3290 (Pacific Time) • Fax 206/647-1445

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Printed in the United States of America

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OPTICS, ILLUMINATION, AND IMAGE SENSING FOR MACHINE VISION V

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A mobile system for measuring retroreflectance of traffic signs

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1. ABSTRACT

There is a serious need for a practical system to evaluate the nighttime visibility of existing traffic signs and provide data for making decisions on sign replacement. A mobile system has been developed which can measure the average retroreflectance of sign legend and background from a moving vehicle during daylight hours. This system uses a video camera to acquire sign images, a xenon flash as a source of light, a personal computer to analyze the sign images, and a laser rangefinder to measure the distance to the sign.

2. INTRODUCTION

The goal of the "Mobile System for Measuring Retroreflectance of Traffic Signs" (MSMRTS) is to permit the measurement of traffic sign retroreflectance during daylight hours, while traveling at speeds up to 55mph. Average values of both sign legend and background retroreflectance, in units of candelas per footcandle per square foot (commonly defined as R') are sought. The task is confounded by the fact that intensity of the retroreflected light from a sign depends on the angle between the source and detector, and this is generally not fixed for realistic dynamic situations. The design must be able to accommodate signs of different colors, shapes, sizes, and placement. The system should be simple and not pose a danger to the operator or other motorists.

The basic concept for the measurement of average legend and background retroreflection is the use of a video camera to record the sign, with an electronic flash source to provide a short burst of light sufficiently bright enough to overcome the sign luminance due to ambient daylight illumination. The video camera signal is then converted to a digitally sampled representation of the sign. Using the power of computer image processing, histograms of the retroreflected intensity distribution are exploited to yield average legend and background values. The use of a laser rangefinder in a moving system provides an accurate means of monitoring the distance from the vehicle to the sign and triggering image acquisition when a predetermined sign distance is reached.

3. BACKGROUND

A retroreflector is a device which turns light back toward its source, usually over a wide range of input angles. Signs are typically comprised of either retroreflective sheeting or retroreflective glass beads mounted directly on the face of the sign. The design of this system has been based largely on retroreflective sheeting. Three types of sheeting are commonly used for highway signs, consisting of enclosed glass beads, encapsulated glass beads, and cube-corner prismatic elements, as shown in Figure 1. The retroreflective properties of these materials are distinctly different from each other, as will be demonstrated later in Section 5.

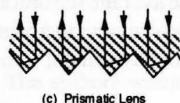
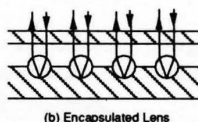
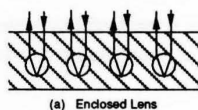


Figure 1.
Common retroreflective materials.

How are these quantities measured? The incident illumination is generally measured using an illuminance meter located at the target and facing the direction of light. A more realistic approach for a mobile system is to use the inverse-square law to infer the illumination from the source intensity, or $E = I/d^2$ where I is the intensity and d is the distance from the source to the detector (assuming that for the distances involved the source behaves as if it were a point). The intensity can be readily calibrated from laboratory measurements, while the distance can be measured using an appropriate laser ranging device. The reflected luminance may be measured with a luminance meter, which is similar to an illuminance meter except that the field of view (FOV) of the detector is limited to a sufficiently small angle. The use of a video camera effectively divides the FOV defined by the system magnification into smaller FOV's, thereby creating individual luminance meters at each sensing element site. In effect, the use of a video camera is a practical way for obtaining a large number of measurement samples from the sign so that representative legend and background retroreflectances may be calculated.

The video system takes advantage of the contrast which typically exists between legend and background, anticipating a "bimodal" reflected intensity distribution. That is, the contrast difference allows the use of simple software algorithms to identify and group areas of similar intensity. For a typical two-color sign, these groups are expected to represent sign legend and background. The average value of each group corresponds to the average luminance, when properly calibrated. Assuming the illumination is known, the retroreflectance is readily obtained using Equation 2.

This approach is illustrated in the histogram plots of video imagery from an actual sign shown in Figure 3(a). This sign image was obtained with the MSMRTS at a distance of 200 feet under sunny outdoor conditions. Software is used to extract the sign area from the image to minimize the influence of pixel values corresponding to the area surrounding the sign. The result of this extraction is indicated by the box drawn in Figure 3(a). The histogram of the extracted sign area is shown in Figure 3(b), plotted as relative number of image points versus reflected light intensity (camera gray levels). First, histogram peaks are isolated, then

The goal of this system is to measure the Coefficient of Retroreflection, or R' , in units of candelas per footcandle per square foot. This can be expressed as:¹

$$R' = \frac{I}{E_n A} \quad (1)$$

where E_n is the normal illumination incident on the retroreflector, A is the area of the surface to be measured, and I is the reflected intensity. By suitable manipulation of these parameters, the retroreflectance can essentially be regarded as the absolute brightness of the retroreflective target for a given amount of incident illumination on the target. Arithmetically, this can be expressed as:

$$R' = \frac{L}{E_n} \quad (2)$$

where L is the luminance of the reflected light. Figure 2 shows the commonly accepted geometry and definitions as prescribed by the American Society for Testing and Materials² for evaluating retroreflective materials.

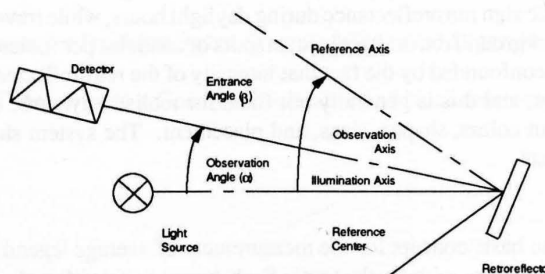


Figure 2.
Plan view of testing configuration showing observation and entrance angles.

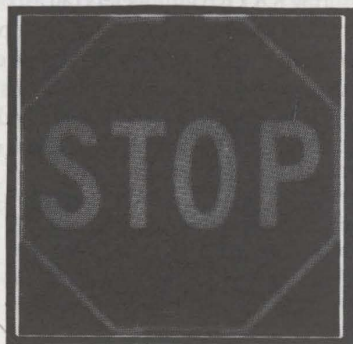


Figure 3(a). Image of typical sign with white legend on black background.

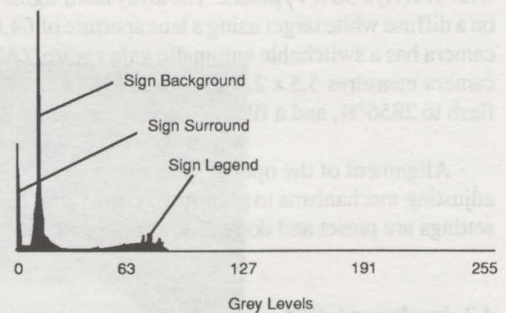


Figure 3(b). Related histogram of image of figure 3(a).

pixels within these peaks are summed to infer the relative area corresponding to each peak. Since signs typically have a larger background area than legend area, the histogram peak with the largest pixel count is considered to be the sign background as shown in Figure 3(b). The region to the right of the sign background peak has a smaller area and is identified as sign legend. The gray levels in these regions are then averaged to obtain sign legend and background retroreflectivities. The gray levels corresponding to image areas surrounding the sign are also indicated in Figure 3(b). The maximum value of sign surround generally does not exceed four gray levels, so excluding these from the histogram analysis is an effective way of obtaining accurate results without the need for sophisticated software to isolate signs having irregular shapes.

4. DESIGN, IMPLEMENTATION AND OPERATION

4.1. Design

The conceptual design for the mobile prototype is shown in Figure 4, with a block diagram of the system components shown in Figure 5. The design centers on the optical head, which mounts on top of the vehicle and which houses the cameras, electronic flash, and rangefinder. The operator is capable of manually aiming the optical head by means of a handle inside the van.

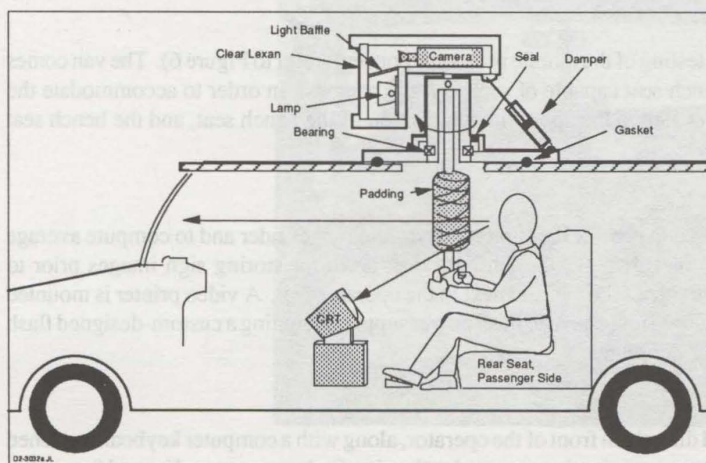


Figure 4. Conceptual design of MSMRTS mobile prototype.

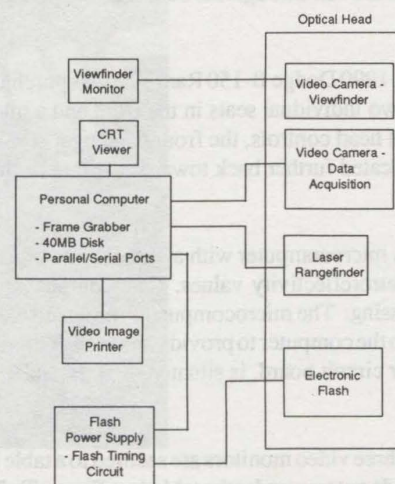


Figure 5. Block diagram of MSMRTS mobile prototype.

In order to satisfy the exposure requirements of this system, an electronically-shuttered video camera having a 1/1000 second duration is utilized. The camera uses a CCD area array measuring 8.8 x 6.6 millimeters (an aspect ratio of 1.33:1) with 491(H) x 384(V) pixels. The array has a signal-to-noise ratio of 46 db (200:1), with a sensitivity of 40 footcandles incident on a diffuse white target using a lens aperture of f/4.0 and a source color temperature of 3200°K (with infrared cutoff filter). The camera has a switchable automatic gain control (AGC) which is disabled since absolute video measurements are desired. The camera measures 5.5 x 2.5 x 3 inches (140 x 64 x 76 mm). A color conversion filter to correct the spectral distribution of the flash to 2856°K, and a filter to correct the camera response to a photopic behavior, are attached to the front of the lens.

Alignment of the optical head components is straightforward. The viewing camera, rangefinder, and flash have suitable adjusting mechanisms to permit alignment with respect to the data acquisition camera, which is fixed. Focus and lens aperture settings are preset and do not require adjustment.

4.2. Implementation

The design and implementation objectives of the mobile prototype were largely driven by physical and ergonomic considerations. The system should be easy to use and require little effort to operate. The system should be designed to permit access to all critical components for maintenance or service. The system should also be capable of withstanding typical environmental conditions such as weather, temperature, dust, and impact (stones, etc.).

The location of the optical head was a primary consideration in the design of the MSMRTS. Locating the head inside the vehicle may create unwanted light source reflections from the windshield and could be annoying to both driver and operator. Locating the head on the vehicle offers the possibility of having separate enclosures for both light source and cameras, thereby eliminating light source reflections off glass surfaces from reaching the camera.

External mounting exposes the system to wind forces which could make the system difficult to control while under way. The front surface area of the top cover and lower flash enclosure is equally distributed above and below the pivot center in an attempt to minimize torque due to frontal wind on the optical head. The entire optical head is balanced by a counterweight located at the rear of the baseplate and a suitably located pivot point. A spherical bearing is used to permit the optical head to swing in the front-to-back direction to control vertical aim and in the left-to-right direction to control camera angle. The bearing also permits the unit to be rotated for horizontal aiming. The unit can be aimed +/- 11 degrees vertically and rotated +/- 90 degrees. Cables are run through the center of the pivot arm to avoid exposure to the weather.

A 1990 Dodge B-150 Ram Van was purchased for testing of the mobile prototype concept (refer to Figure 6). The van comes with two individual seats in the front and a middle bench seat capable of seating three persons. In order to accommodate the optical head controls, the front passenger seat was relocated to the approximate location of the bench seat, and the bench seat was located further back towards the rear of the van.

A microcomputer with a video frame grabber is used to control the camera, flash, and rangefinder and to compute average sign retroreflectivity values. The computer has a 40 megabyte 3 1/2 inch hard disk drive for storing sign images prior to processing. The microcomputer is mounted close to the side of the van and next to the operator seat. A video printer is mounted next to the computer to provide hard copy output of the video images. The flash power supply, including a custom-designed flash trigger circuit board, is situated directly underneath the computer.

Three video monitors are secured to a table located directly in front of the operator, along with a computer keyboard attached to a slide out tray under the table (see Figure 7). The leftmost monitor is connected to the viewfinder camera and is used for aiming the optical head at the oncoming sign. The monitor in the center is connected to the video frame grabber and is used to view the sign image used for the data analysis. The rightmost screen is connected to the computer and serves as the system monitor.



Figure 6. Exterior photograph of MSMRTS.



Figure 7. Interior photograph of MSMRTS looking toward the front.

The power for the computer, flash, and monitors is derived from an inverter (made by Vanner, Inc.) which converts 12 volts DC supplied by the vehicle to 120 volts AC. The inverter is capable of supplying 1,000 watts continuously and is sufficient for supplying the needs of the system. The inverter is connected to two deep-cycle 12 volt batteries which act to store energy and effectively minimize the duty-cycle of the vehicle alternator. An isolator is used to prevent the vehicle battery from being discharged inadvertently. A voltmeter is located on the dashboard to monitor the state of the inverter batteries.

4.3. Operation

Figure 8 summarizes the operational scenario of the MSMRTS. The operator aims the optical head at an oncoming sign with the help of a video monitor attached to a wide angle video camera. The operator then presses a button located on the operator control handle to initiate rangefinder measurement software. The operator continues to "track" the sign in the video monitor, allowing the rangefinder to continuously measure the distance to the sign. When a predetermined sign distance (200 feet in "highway" mode, 100 feet in "local" mode) is reached, the computer triggers the electronic flash and the frame grabber acquires a video image from a second, narrow angle, video camera. The operator then may enter sign information (approximate milepost, route, and heading - or major street and cross-street) and the system stores this data together with the image and a file number for later identification. At the end of the run, the files are then analyzed to determine average legend and background retroreflectance for each sign and the results are printed on the screen. A video image printer is used for making hard copies of the resulting image for reports. Approximately 135 images may be stored before processing is required, although it is anticipated that minor software changes will increase the maximum capacity to 270 images.

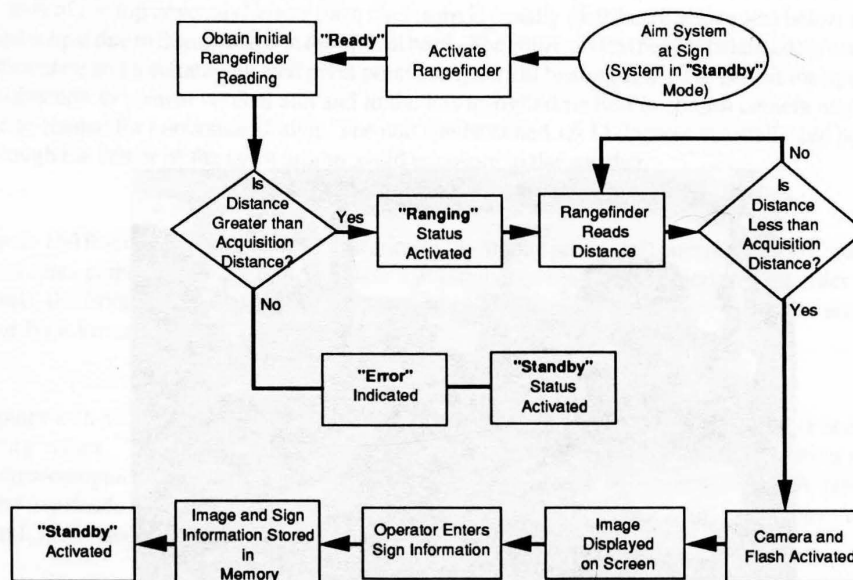


Figure 8. MSMRTS operational scenario.

5. FACTORS AFFECTING ACCURACY

5.1. Measurement geometry

In a system designed for in-situ measurements, the design of a system to achieve a specific measurement geometry is straightforward. In a moving system, the geometrical relationship between source, sign, and detector is constantly changing. Attention to this relationship is important since, in general, all retroreflective devices do not behave the same as the geometry is changed. The geometries of concern are observation angle and the entrance angle, as demonstrated previously in Figure 2.

Retroreflective materials are highly directional upon retroreflection, with prismatic sheeting most highly directional, followed by encapsulated and enclosed materials (refer to Figure 9). Assuming a fixed source-detector separation, the observation angle increases with decreasing distance to the sign. Realistically, the material of the sign being measured will most likely not be known, so that unless the angle is kept constant, or nearly so, for all situations, it will be nearly impossible to relate the measured value to a commonly measured observation angle (such as 0.2°). Hence, in order to maintain sufficient accuracy, there is a "distance window" in which the measurements need to be taken, assuming a fixed source-detector separation.

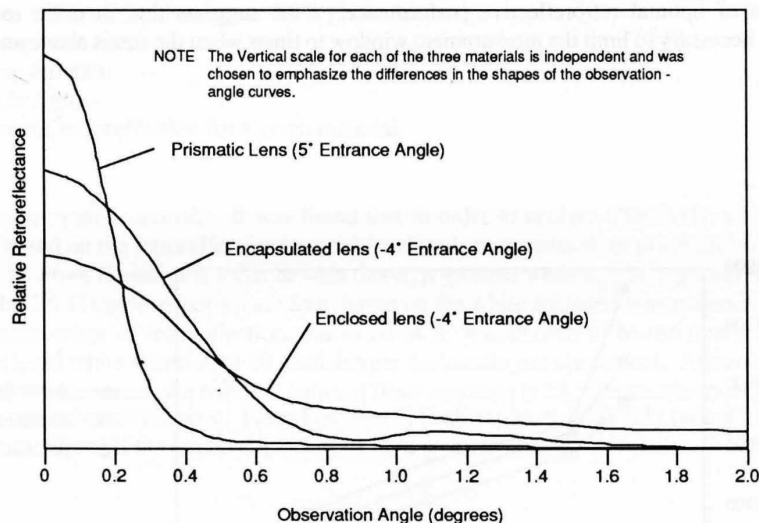


Figure 9. Relative retroreflectance versus observation angle.⁴

The effect of entrance angle (the angle between the axis of the light source and the normal to the sign) is far less severe. Generally, the reflected intensity falls by a worst case approximation of 1% per degree out to about 20 degrees for prismatic materials. In moving situations, it would be very difficult to measure the entrance angle. However, it can be expected that the entrance angle of most signs at appreciable distances is small, minimizing this effect. This angle is nearly the same for the measurement system as for the driver, so the impact of entrance angle on sign retroreflectivity is a realistic assessment of the sign's performance. Thus, compensation for entrance angle is not considered in the measurement system.

5.2. Ambient illumination effects

Since daylight measurements are required, it is necessary to either eliminate the effect of ambient illumination, or reduce the effect to a point to which it becomes tolerable with respect to the desired accuracy of the measuring system. Retroreflective effectiveness is usually relevant over small observation angles, and published measurements typically give data out to about 2° . However, retroreflective materials exhibit a small but appreciable coefficient of retroreflection at large observation angles (the angle subtended by the light source and the detector at the sign), as shown in Figure 9. For instance, the R' for enclosed-lens white materials is typically 100 - 120 at a 0.2° observation angle, but generally levels off to a value of approximately 0.3 at angles beyond 20 degrees. Ambient illumination levels can be quite high, approaching 10,000 footcandles for combined sun and clear sky, effectively offsetting the low R' value at large angles and creating appreciable daytime sign luminance levels.

In order to determine the effect of ambient illumination on sign luminance, samples of white enclosed, encapsulated, and prismatic materials were measured at various sun elevation angles. Measurements of sample luminance were taken with the plane of the material oriented vertically, but always in a direction facing closest to the sun. The experimental data shown in Figure 10 indicates that at any given angle, the enclosed-lens white material has the maximum luminance, followed by prismatic and encapsulated materials. At an angle of 20 degrees, the maximum ambient sign luminance was found to be 2,500 candelas per square foot for enclosed materials, 2,100 candelas per square foot for encapsulated materials, and 2,300 candelas per square foot for white prismatic materials. For solar angles less than 20 degrees, the rate of change of the ambient luminance increases more rapidly. This should be expected since the sun is creating a smaller observation angle with respect to the detector and thereby approaching the region of optimal retroreflective performance. This suggests that in order to minimize illumination requirements, it may be necessary to limit the measurement window to times when the sun is above an elevation of 20 degrees.

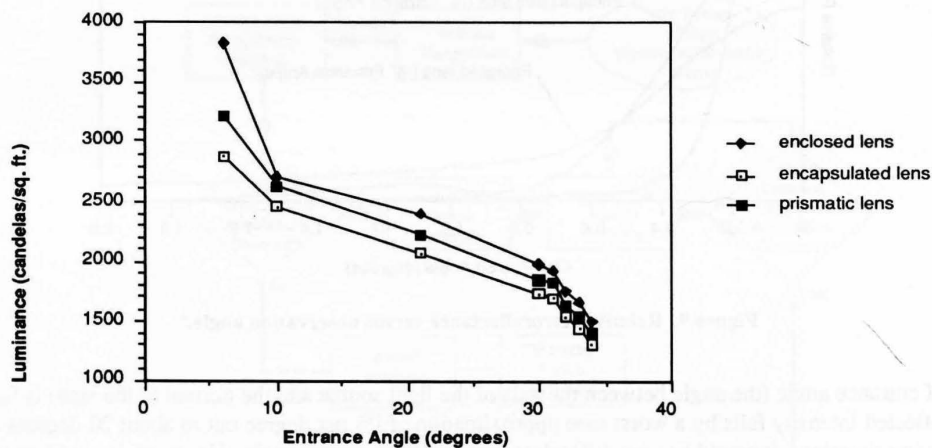


Figure 10. Sign luminance versus solar elevation for enclosed, encapsulated, and prismatic lens materials (white).

5.3. Intensity requirements

For a uniform retroreflective target possessing a given luminance due to ambient illumination, the light source must provide an adequate amount of additional exposure above the ambient signal so that the retroreflection due to the illumination system may be appropriately detected and isolated. This additional exposure factor can be denoted by a constant K. The value of K selected determines the capability of the system to reject the sign luminance due to ambient illumination. For example, a value of 20 implies a 20:1 ratio of artificial to ambient signal, and hence the measured data will have a 5 percent maximum error due to the presence of an ambient signal. The value of K could be as high as the signal-to-noise ratio of the camera, typically 200:1 for CCD cameras, but the additional demands required of the illumination system may not be realistic.

For electronic flash sources, the intensity is not constant over the duration of the flash. For this reason, it is customary to specify flash intensity in terms of an integrated value, denoted by I_t . It can be shown that this required "intensity exposure," to produce the necessary detection may be expressed as:³

$$I_t = \frac{K L_{amb} t_{cam} d^2}{R'} \quad (\text{for } t_f < t_{cam}) \quad (3)$$

where L_{amb} = maximum ambient sign luminance for a given material
 t_{cam} = camera exposure time
 t_f = flash lamp duration
 d = distance to sign
 R' = coefficient of retroreflection for a given material.

The units for I_t are in candela-seconds. It was found that in order to operate effectively with all materials, intensity requirements should be based on the retroreflective material (enclosed, encapsulated, or prismatic) which produces the worst case, or largest value of I_t . From Equation 3, it can be seen that I_t is greatest when L_{amb} is large and R' is small. From Figure 10, L_{amb} was chosen to be 2,500 candelas per square foot, based on the white enclosed-lens material. Furthermore, to obtain accuracy over a reasonable range of retroreflection, the value of R' was chosen to be the minimum recommended value corresponding to the enclosed white material, or 70 candelas per footcandle per square foot. Assuming a K value of 20 and a camera exposure time of 1 millisecond, the required value of flash exposure is 28,500 candela-seconds, as long as the flash duration is less than the camera exposure time. From Equation 3, flash exposure is directly proportional to K, indicating that system accuracy will be sacrificed if the required quantity of light is not available.

5.4. Electronic flash

The advantage of using an electronic flash is that large quantities of light are produced over short periods of time. For maximum efficiency, the flash duration should be less than or equal to the exposure time of the camera.

As Equation 3 indicates, exposure requirements are minimized when t_{cam} is short. It would, therefore, seem desirable to reduce t_{cam} as much as possible. However, as t_{cam} is reduced, the flash exposure time, t_{flash} , must be reduced as well. In general, there is an optimum flash duration in which light output efficiency is maximized for a given flashtube design. Also, the necessity for an appreciable quantity of light for this application generally requires a relatively long flash duration (on the order of 0.1 to 1 millisecond), but in moving situations, the duration needs to be short enough to "freeze" the effects of image motion due to vibration.

The electronic flash used in the MSMRTS has a duration of approximately 1 millisecond and produces 40,000 candela-seconds, nearly 40% greater than the 28,500 value described above. The spectral quality of electronic flash units are generally found to be in the daylight region of the spectrum, with typical color temperatures ranging from 5,000°K to 7,500°K, depending primarily on fill gas, pressure, and energy loading. The output is nominally continuous with few spikes which may adversely affect color measurement accuracy. The unit uses a long linear flashtube in a trough-type reflector having a parabolic cross-section, yielding a long, but narrow beam profile. In the more critical vertical direction, the total beam spread, defined at the 90% points, was measured to be approximately 2°.

5.5. Rangefinder accuracy

A commercially-available laser rangefinder is used to obtain sign distance information. This device uses a time-of-flight (TOF) method in which short pulses of laser light supplied by a laser diode are sent out to the target. By measuring the time to receive the returned pulse, and knowing the speed of light, the total round-trip distance can be calculated. This value is divided by two to obtain the actual distance to the target. The rangefinder operates at a sampling rate of 2,000 samples per second, but in order to improve measurement accuracy, the unit can average a number of samples to obtain the distance reading. The number of samples per reading is called the repetition rate. The 9,600 baud data rate of the serial interface limits the effective data transfer to approximately 133 readings per second, or 15 samples per reading, with a net estimated accuracy of ± 0.27 feet (± 82 mm) under stationary conditions. At a constant speed of 40 mph (59 feet per second), the resulting distance resolution is estimated to be 0.30 foot. Experiments indicate that the accuracy of sign measurements taken at 40 mph is within 2% of measurements obtained while stationary. Measurement variability at 40 mph is found to increase by less than 1% over stationary measurements.

5.6. Image processing

The MSMRTS measures a fixed size region which is generally centered within the sign. Due to the differences in sign size, the image processing may have difficulty distinguishing between the dark background or legend and the image area surrounding the sign. This typically results in the determination of an incorrect threshold for the sign, producing an erroneous partitioning of legend and background regions. If this occurs, the result is easily observed since the video monitor displays an incorrectly thresholded image. The software has a feature permitting the operator to manually select the desired sign region or manually change threshold settings.

6. EXPERIMENTAL RESULTS

Ten signs were measured with the mobile system and compared to data obtained with a calibrated hand-held retroreflector. The signs used for this experiment had a white background color with background R' values ranging from approximately 4 to 350. Calibration of the system was accomplished by acquiring an image of a calibrated white sheeting material and computing a scale factor to convert the 8-bit digital gray levels of the calibration target image to R' values. Sixteen image samples were obtained for each sign using an observation angle of 0.2° and at a distance of 200 feet ("highway" mode). The same signs were measured by an Advanced Retro Technology 910F hand-held retroreflector (HHRR) calibrated with the same calibration target used to calibrate the MSMRTS. Six randomly distributed HHRR measurements of the sign background were made for each sign.

Figure 11(a) summarizes the comparative results of the MSMRTS and HHRR. Figure 11(b) shows the differences as a percent of the full scale (% FS) MSMRTS reading, where full scale was found to be 378 R'. From the graphs, it is evident that the results are in close agreement with measurements made with the HHRR. The MSMRTS measurements were found to be typically within

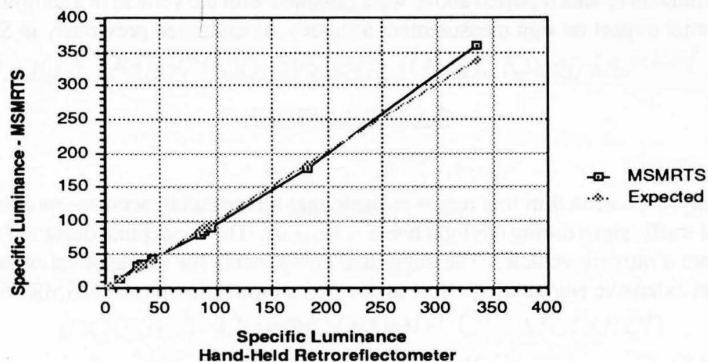


Figure 11(a). MSMTRS (maximum 378 R') versus hand-held retroreflectometer measurements.

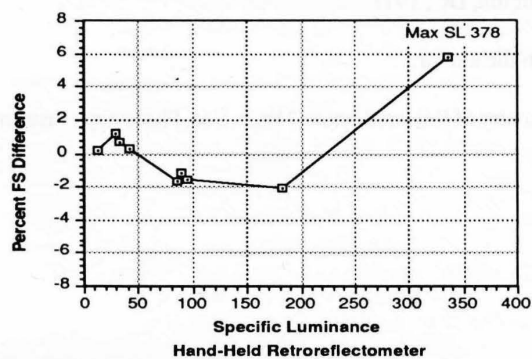


Figure 11(b). Percent difference of MSMRTS (maximum 378 R') compared to hand-held retroreflectometer.

3% FS of the HHRR measurements. It should be noted that differences between the MSMRTS and the HHRR are expected, since it may be difficult to obtain a representative average measurement for a sign which has sufficiently nonuniform retroreflectivity.

The data for the experimental results reported above were obtained with the vehicle in a stationary position. Vehicle speed is expected to have a minimal impact on sign measurement accuracy, as discussed previously in Section 5.5.

7. CONCLUSIONS

The research and analysis presented in this report indicate that a reasonably accurate mobile system for measuring the average retroreflectance of traffic signs during daylight hours is feasible. The conceptual design of the system is well suited for making measurements from a moving vehicle. The suggested components for this application are commercially available, minimizing the need for an extensive engineering effort to develop a production model MSMRTS.

8. ACKNOWLEDGMENTS

This work is being sponsored by the National Cooperative Highway Research Program (NCHRP) which is administered by the Transportation Research Board of the National Research Council, Contract No. HR 5-10.

9. REFERENCES

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