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Empirical Characterization of a High Intensity LED Proximity Sensor

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EMPIRICAL CHARACTERIZATION OF A HIGH INTENSITY LED PROXIMITY SENSOR

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ABSTRACT

Many robotic operations require accurate and precise distance measurements to arbitrary targets in an unstructured environment. Such information can be used in path planning, object avoidance, surface following, topological mapping, relative positioning, artifact resolution, etc. Hence, there is a significant need for a non-contact proximity sensor system which is minimally effected by target composition, orientation, color, texture, etc. and to empirically understand its behavior with respect to such target characteristics. This paper describes a most promising sensing technology (high intensity LED triangulation) and presents an empirical analysis of a representative, commercial system.

1. INTRODUCTION

Many robotic operations require very accurate control in grasping, near contact or close proximity conditions in an unknown environment. Such tasks include object handling, environmental surveying, target monitoring, imminent object avoidance, etc. These operations require a non-contact proximity sensor system which achieves a high level of accuracy irrespective of the target's intrinsic character, e.g., texture, color, orientation, size, composition, etc.

To be generally useful, the sensor system must minimize its assumptions about the environment. Unfortunately, this minimization places tremendous demands on the technology employed by the proximity sensor system; most non-contact proximity sensor technologies require the target to exhibit some special characteristic which may not be realistic. For example: inductive and capacitive sensors place strict requirements on the target's basic composition; thru-beam photoelectric sensors place strict limits on the target's position and size and the system's control capability (since these sensors are boolean); and ultrasonic sensors require the near perpendicularity of the target's surface.

To determine the best, currently available technology for our application: gross motion planning and control in an unconstrained environment, the various, potentially limiting, characteristics were prioritized. It was determined that an effective, non-contact, proximity sensor must maintain accuracy to within about 0.1" despite: widely varying target textures, colors, and compositions; sizes down to ~0.25 sq. in.; and target orientations of up to 45° off perpendicular. Furthermore, the sensor must perform over a range of several inches and rapidly update its output (>100Hz.). The ability to handle objects of unusually high gloss, transparency, or sound absorption was not deemed vital due to their atypical nature. Based on these guidelines, high intensity LED triangulation was determined to be the most applicable sensor technology.

The following section describes this technology and characterizes a sample sensor system. Section 3 discusses the testing procedures used to analyze this sensor's performance and empirical results. Conclusions are given in Section 4.

2. SENSOR

A high intensity LED triangulation sensor system was obtained from the Spectronics Corporation for testing: the Spectronics Model 204-4.0, see Fig. 1. This system emits a beam of visible light which is reflected off nearby targets and measured by an on-board sensor, see Fig. 2. The receiving system screens-out ambient light with its proprietary optics and determines the target's distance by triangulation based on the angle of the returned signal. This angle is determined by the incident position of maximum returned energy on a linear photo-electric detector. Spectronics further reduces the effects of ambient light by pulsing the emitted signal, measuring the background light level during non-broadcasting periods, and scaling the reflected readings accordingly. Changes in target reflectivity are addressed by dynamically alternating between two levels of emitted signal intensity based on the magnitude of the detected signal. These various features permit the Spectronics system to be largely unaffected by changes in color, ambient light, and most importantly, orientation.

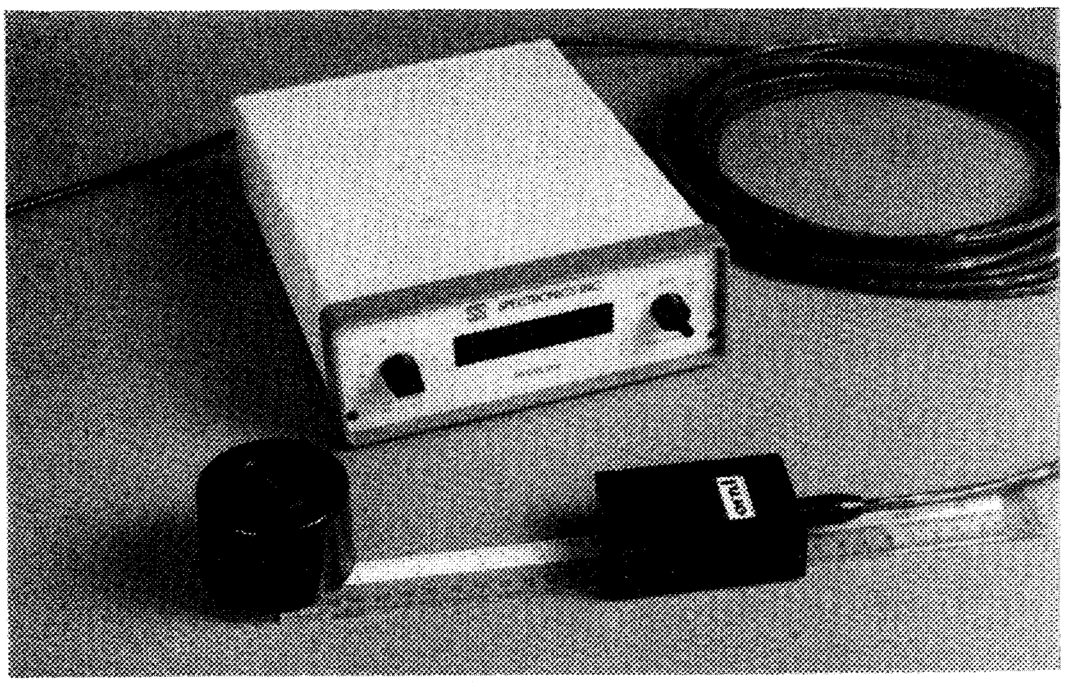

Fig. 1. Spectronics Model 204-4.0 Close Proximity Sensing System.

Active sensor systems, i.e., those which detect their own reflected transmission, are necessarily limited by the reflectance characteristics of their target. Hence, just as a sonar system is "blind" to sound absorbing surfaces, a light emitting system is "blind" to highly reflecting/absorbing surfaces. This limitation will be empirically explored in Section 3.

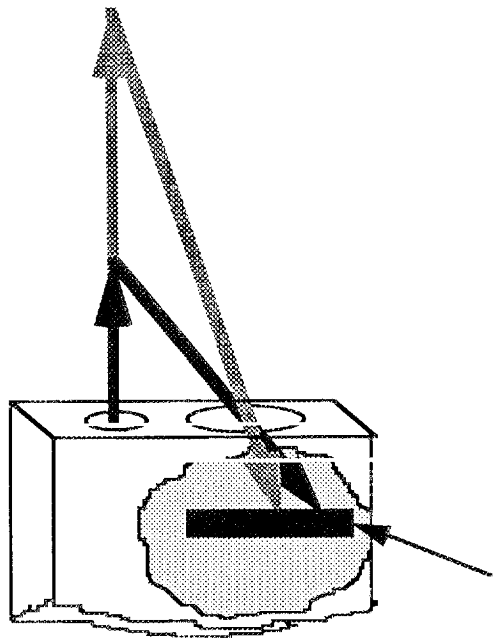

Fig. 2. High Intensity LED Triangulation System.

The following tables present the basic specifications claimed by Spectronics for their Model 204-4.0.[1] This sensor system consists of three units: the control box which houses the decoding electronics, the sensor module from which the target is measured, and a connecting cable. The control box and sensor module must be tuned as a system and, hence, are not interchangeable. Table 2.1 presents the basic physical data associated with each of these components, while Table 2.2 presents the claimed capabilities/limitations.

Table 2.1. Spectronics Model 204-4.0 – Physical Specifications

SENSOR MODULE:	1"H × 2"W × 4.1"L
CABLE:	30 feet standard
(Available in any length, though not tested > 150 ft.)	
CONTROL BOX:	2.75"H × 7.25"W × 9.25"L
CONTROL BOARD:	~1"H × 7"W × 7.5"L
(in lue of control box)	
Input Power:	120 VAC, 60Hz, @0.75Amp
or	+5, +15, -15 VDC @ 200mA (without power supply)
Data Output:	RS-232C, Analog 0-10 VDC, and Digital Display
Selectable Measurement Mode:	Absolute or Differential
Display Refresh Rate:	0.5, 1, 2, 4, or 8Hz
Baud Rate:	300 to 19,200 baud
(user selected data output rates)	
Footprint Size:	0.004" × 0.020" oval

Table 2.2. Spectronics Model 204-4.0 – Capabilities/Limitations

Stand-Off Distance:	4.0 inches
Measurement Range:	±2.0"
Accuracy:	±0.015"
Repeatability:	0.0075"
Measurement Rate:	250 Hz
Temperature Operating Range:	0°C to 50°C
Relative Humidity:	To 90% non-condensing

Note: Spectronics verbally expected difficulty with glossy surfaces and incident angles of greater than 40°–45°.

3. EMPIRICAL ANALYSIS

For our application, autonomous robotic control systems must understand their close proximity environment with a distance accuracy of at least 0.25". This accuracy must be maintained regardless of the targets encountered and their orientations. By fully understanding a sensor system's actual responses to real-world events, control software can be designed to exploit their strengths and minimize their weaknesses. Hence, proper empirical characterization is essential to maximize a sensor system's effectiveness in a real-world robotic application.

Target objects must be carefully chosen to minimize simultaneous trait effects and isolate individual characteristics for analysis, e.g., to understand the effect of color on the sensor system, only solid colored items, of similar material, should be employed. Additionally, a number of other physical characteristics are logistically required of the target objects, including: size appropriate for the experimental facility; veracity, i.e., the ability to accurately determine position truth, e.g., target perpendicularity, smoothness, etc.; and ruggedness, to provide consistent performance over multiple tests. With these guidelines, a suite of objects were chosen which provide colors ranging from black to white and sheens from flat to heavily glossed. These objects were used to characterize the Spectronics Model 204-4.0 sensor system. (Note that since each Spectronics controller is individually tuned to its sensor's optics, the actual performance of other Spectronics sensor systems may vary.)

3.1 MODE OF OPERATION

A sensor system's accuracy may depend not only on intrinsic characteristics of the target, e.g., color, gloss, etc., but also on the geometric factors of distance, orientation (angle of incidence), relative size and shape. The relative size and shape of the target is not considered a problem for the Spectronics sensor system due to its extremely small footprint size (~0.00006 of a square inch), except at sharp distance discontinuities. Hence, our empirical analysis concentrates on these remaining factors: color, gloss, distance, orientation, and sharp distance discontinuity. A set of large, planar targets (each exhibiting a different color and gloss level) are employed in three experimental modes: varying distance, varying orientation and scan. To improve empirical accuracy, statistical averaging is employed throughout.

1) **Varying Distance** – In this mode, the distance between the sensor and the target is varied and truth is compared with the system's measured value, see Fig. 3. This mode is used to characterize system accuracy versus distance for each target type, e.g., flat blue, gloss black, etc. In distance mode, truth is accurate to ~0.001".

2) **Varying Orientation** – In this mode, the angle of incidence between the broadcast signal and the target's surface is varied while the distance to the target is held constant, see Fig. 4. Thus, an analysis of the sensor system's output will reveal its dependence on the target's orientation for each of the various target types. (Note that since the signal path is asymmetric, orientation changes corresponding to pitch and yaw may have different effects and must be analyzed independently.) The equipment used in this experiment was accurate to within ~0.5° in orientation and ~0.001" in placement. Unfortunately, for large angles, 0.001" placement error may translate to a substantial target distance error, see Fig. 5. As the angle of incidence approaches 90°, the true target distance becomes less accurate and reliable characterization more difficult.

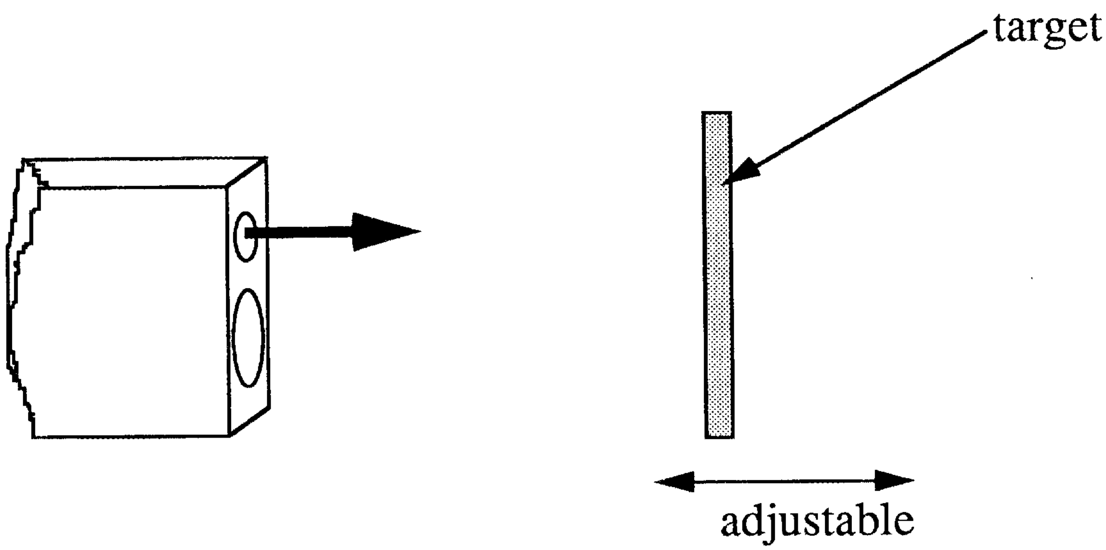

Fig. 3. Distance Mode.

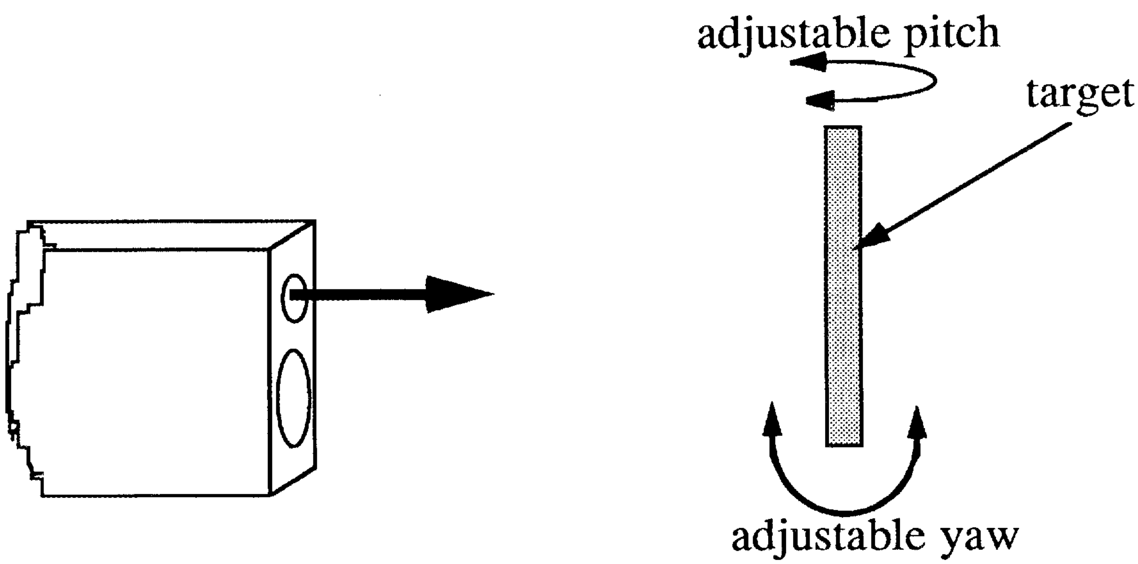

Fig. 4. Orientation mode.

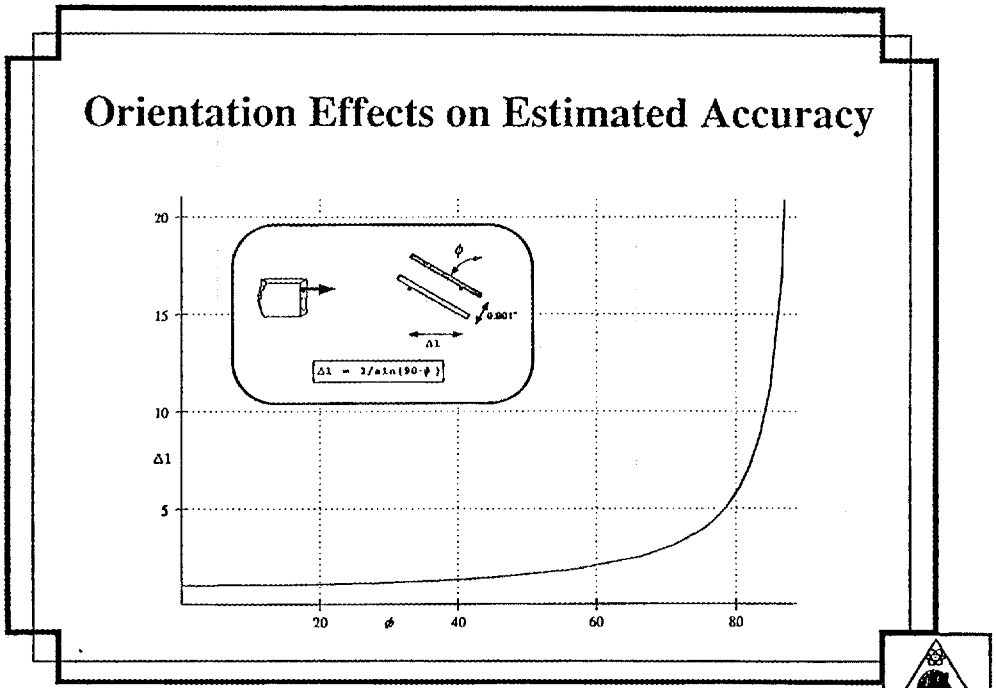

Fig. 5. Truth inaccuracy vs. orientation.

3) **Scan** – Generally speaking, the goal of the sensor system is to output the distance from the front surface of the light beam emitter to the beam's strike-point on the target. However, if the target's surface is not of uniform distance over this footprint, satisfaction of this goal is impossible to define. One way to minimize the magnitude and likelihood of a problem occurring is to reduce the actual footprint size. However, as long as the footprint has a non-negligible area, it is possible for it to strike multiple target distances, e.g., at a sharp surface discontinuity or edge.

Inconsistencies between truth and the sensor system's output during sharp distance transitions are known as the system's edge effects. The sensor system's handling of edges must be fully understood to properly interpret the sensor's data and, hence, the robot's environment.

Edge effects are measured by scanning the sensor's footprint across a clearly defined transition between parallel partial planes of different distances, see Fig. 6. During the transition from one plane to the other, the system output is compared with truth to expose inconsistencies (edge effects). These experiments have a lateral scan resolution of 0.015" with a placement accuracy of ~0.001".

3.2 EMPIRICAL RESULTS

The three modes of experimental operation described above provide the basis for determining the suitability of this sensor system to our robotics application. Included in this analysis are the effects of distance and orientation on the system's accuracy across a full range of colors and glosses as well as inherent edge effect anomalies.

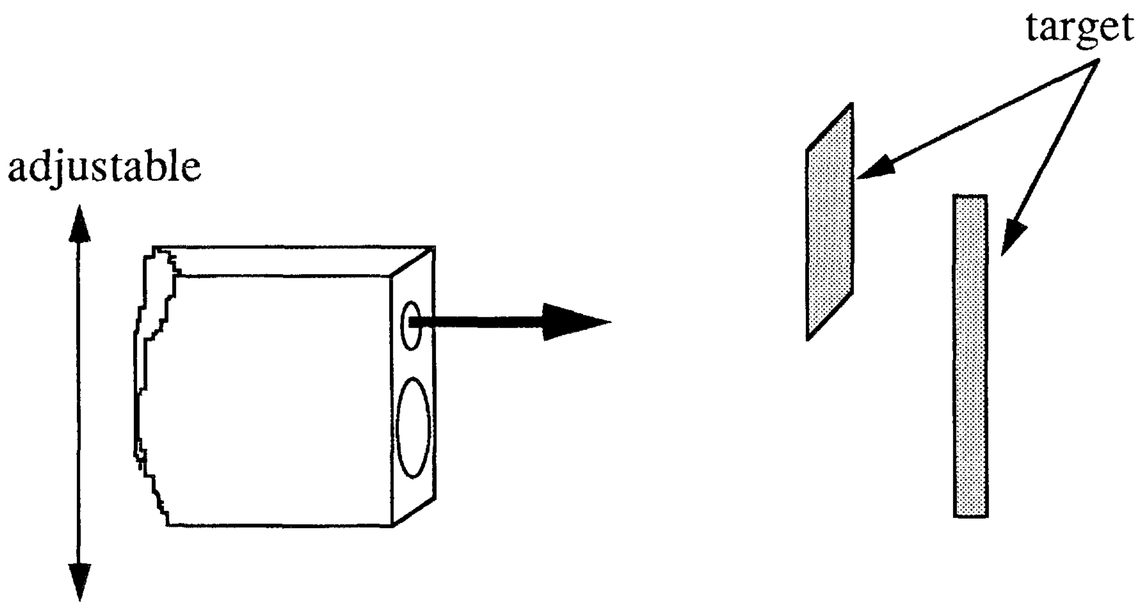

Fig. 6. Scan mode.

3.2.1 Distance

The first set of experiments characterize the sensor system's ability to measure the distance to various orthogonal targets. Figure 7 plots the sensor's output versus truth for a representative set of these targets. Note that Spectronics only claims its sensor system is functional for target distances between 2" and 6".

Two important results should be noted from this experiment. First, except for gloss black (electrical tape), all of the targets performed accurately within the range ~2.2" - ~6.4", including all colors and gloss levels. Second, all targets induced a temporary increase in readings as the true distance approached its lower bound. This behavior apparently resulted from a hardware design error which causes a wrap-around of the received signal on the linear position detector. This problem may have been more severe for gloss black, since gloss black required the use of the higher, turbo mode signal intensity. Spectronics was informed of this erroneous behavior and has corrected the design — subsequent units do not exhibit this behavior.

3.2.2 Orientation

Two types of orientation are possible due to the asymmetry of the sensor body: yaw - rotation in the plane of the emitter and receiver; and pitch - rotation in a plane perpendicular to that of the emitter and receiver. All targets were placed so that the sensor's footprint would strike the target's pivot point 4.0" from the sensor. Thus, we can characterize the system by comparing the output's deviation from 4.0" as a function of the angle of rotation.

Figure 8 plots the sensor reading versus pitch angle for a representative set of targets. Note that Spectronics only claims an accuracy of 0.015" for angles up to ~45° for most non-glossy colors. In general, this system performed substantially better. Most targets were within 0.003" for angles up to ~80°. (Recall that the measurement of truth is very inaccurate for angles above ~80°, see Fig. 5, and would

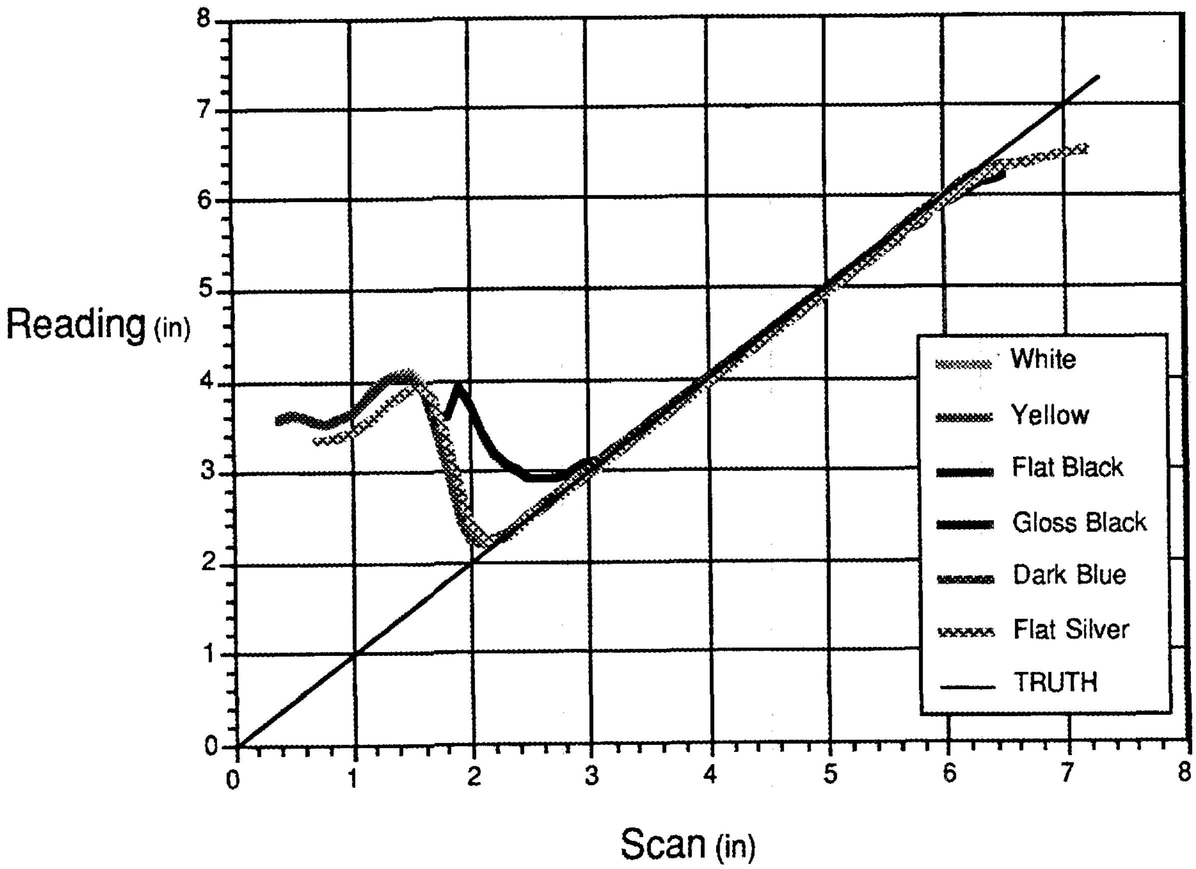

Fig. 7. Output vs. distance.

account for the apparent fanning of the data in this region. Hence, the system may actually be accurate to nearly 90°.)

Gloss black is the only target that had a severely restricted range of orientations: $-10°$ to $\sim +20°$. Since gloss red was effectively measured from $-80°$ to $+86°$, the fault with gloss black appears not to be its high sheen, but rather its combination of high reflectivity and high light absorption.

Figure 9 plots the sensor reading versus yaw angle for a representative set of targets. Note that a physical limitation of $\sim -78°$ is caused by the relative positions of the emitter and receiver on the sensor body, see Fig. 2. Though the system is clearly less accurate for yaw than for pitch, it still performed well within the expected range of accuracy and handled angles well beyond the claimed limits. As with the pitch, the fanning of the data may only indicate an error in measuring truth. The difficulty with gloss black is also evident in this experiment.

3.2.3 Edge Effects

This experiment analyzes the system's ability to accurately measure a sharp discontinuity in target distance, e.g., a boarder or edge of a target. Figure 10 plots the sensor reading versus the lateral position of the sensor body as it is scanned across a sharp discontinuity at various initial offsets, see Fig. 6.

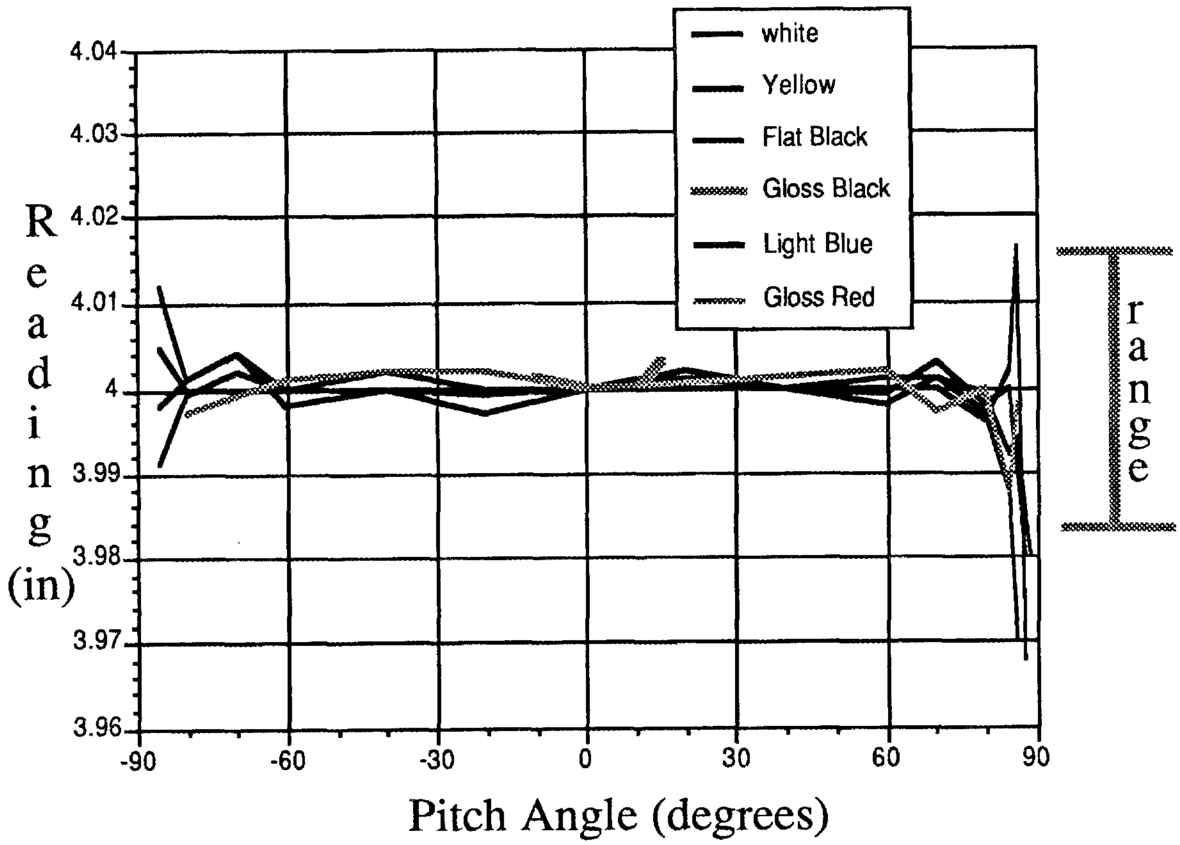

Fig. 8. Output vs. pitch angle.

In Fig. 10, the sensor readings obtained at lateral position 0 and 0.05 reveal the true distance to the first (near) surface and the readings obtained at lateral position 0.15 and 0.20 reveal the true distance to the second (far) surface. (Note that the same edge was scanned for each of the twelve curves shown in Fig. 10, with only the initial sensor to surface offset being changed. Hence, the difference between the initial reading (at position 0.0) and the final reading (at position 0.20) is a constant (0.78)—the true distance between the two surfaces).

An edge effect is clearly seen at scan position 0.1; the reading is neither that of the near surface nor the far surface. There are two important characteristics to note in this figure. First, while the scan resolution of 0.05" is sufficient to reveal the edge effect, it is too coarse to indicate its true span. That is, this data only bounds the span of the edge effect to less than 0.1", (it occurred completely between scan position 0.05" and 0.15"). The effect may actually be much narrower. Second, the edge effect seems to be a function of signal distance. Unfortunately, one can not determine whether increased distance delays the edge effect or decreases its span. If the former is true, then the near non-detection of an edge effect for offsets $>\sim$ 4.0" indicates that the effect's actual span is less than 0.05".

To better understand this effect, the resolution was increased to 0.015". Figure 11 plots the average reading and standard deviation over ten runs. This figure indicates the edge effect span is less than 0.06". The spread in the standard deviation may be completely due to experimental error since the stability of the sensor's reading is a function of the consistency of the target's distance in and around the sensor's footprint, i.e., the relative smoothness of the target in and around the footprint directly effects the impact of minor placement errors on the sensor's reading.

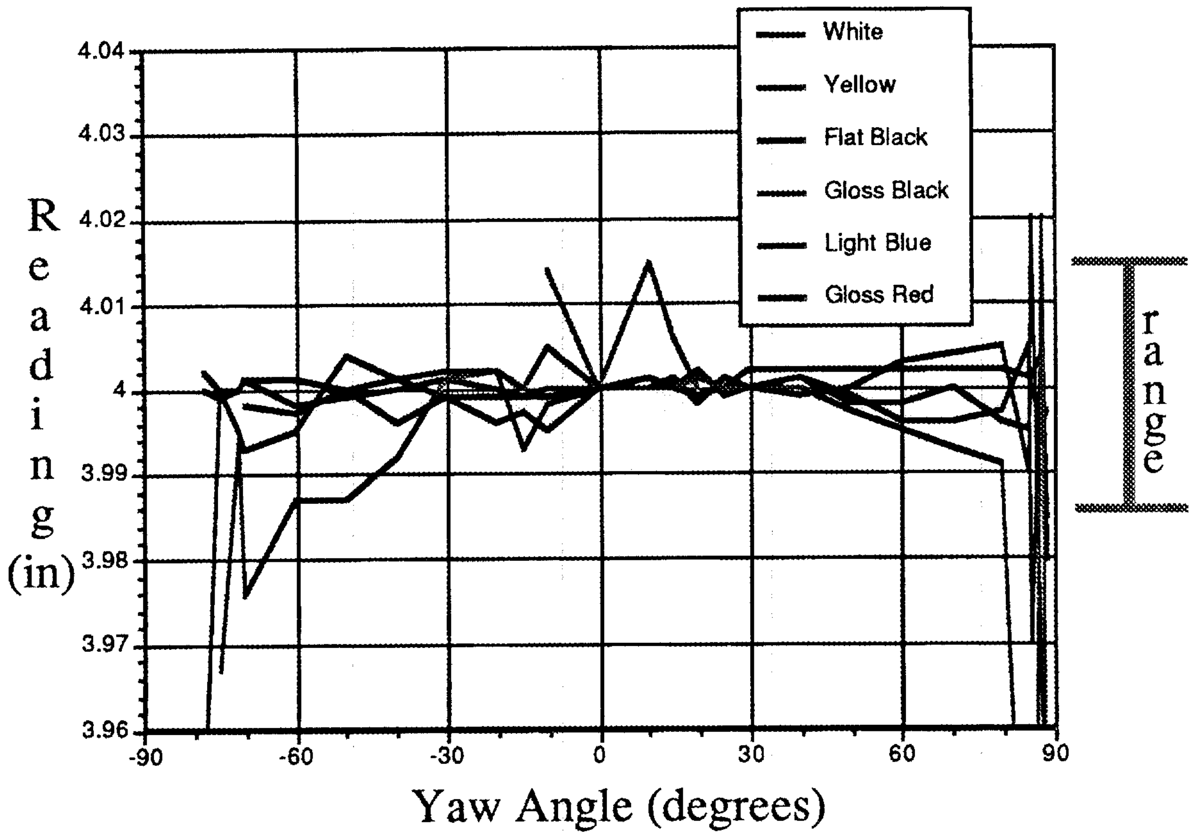

Fig. 9. Output vs. yaw angle.

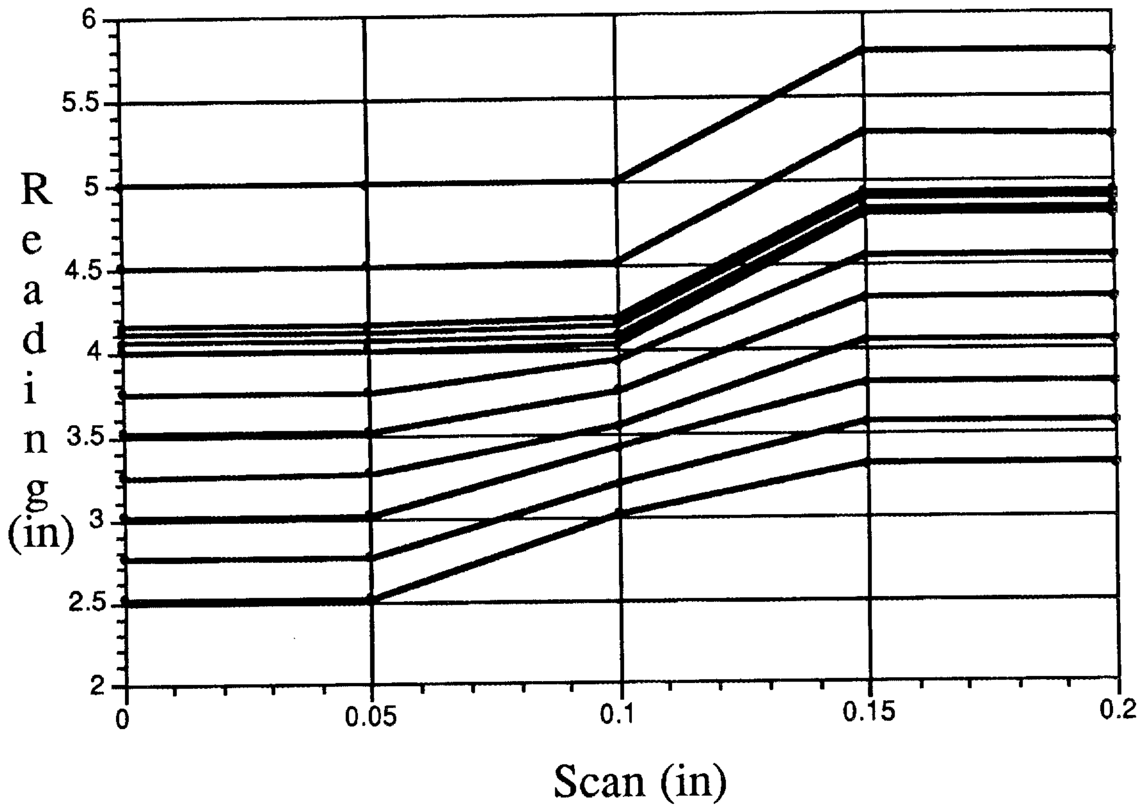

Fig. 10. Output vs. relative scan position.

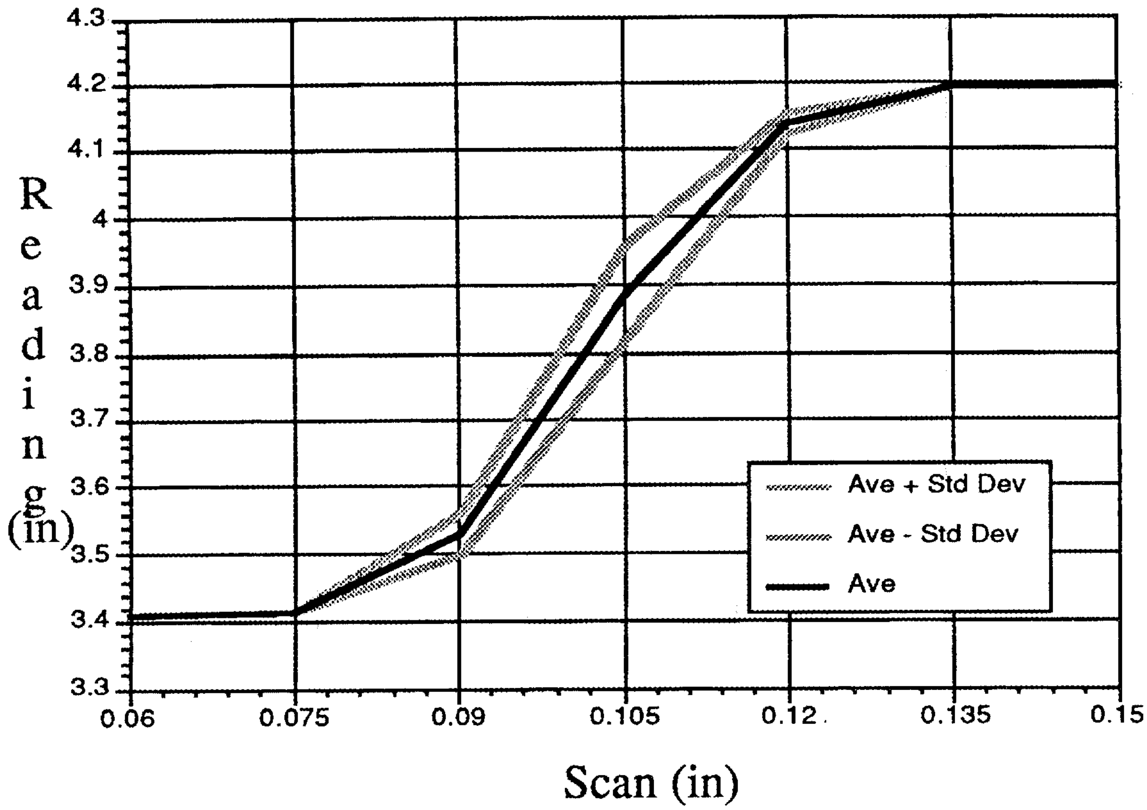

Fig. 11. Average output vs. relative scan position.

4. SUMMARY

Overall, this system performed better than expected and, in most cases, significantly better than required for our robotic application. Due to the inherent physical imprecision of humans, robots, and their environments, close proximity accuracy of only ~0.1" is needed. This sensor system's ±0.015" average accuracy is an order of magnitude better and should provide a useful margin of safety. However, this system's most impressive capability is its accurate detection of targets which are over 80° off perpendicular. The importance of this capability can not be over emphasized in any application with an unstructured environment. Furthermore, this capability is largely lacking in most of the competing technologies, e.g., comparative SONAR systems have a much smaller angular detection range.

The Spectronics Model 204-4.0 sensor system has two basic problem areas: close-range detection, i.e., <2.25"; and glossy black surfaces. In close-range detection, an internal wrap-around error effectively limits the sensor system to the range 2.25" to 6.25" for non glossy black targets. Although Spectronics has corrected this problem in their new system design, they still exhibit a non-monotonic nature within 2" of the target. This behavior could present significant problems for a robotic control system.

Glossy black targets cause several problems: a limited orientation range (~30°), a limited distance range (~3"), and less accuracy (±0.046"). Since both gloss red and flat black experienced no performance degradation, the problem does not seem to lie solely with either the color or the gloss level. Unfortunately, while gloss black is admittedly the most difficult combination, it is not uncommon in real world applications.

5. CONCLUSIONS

The Spectronics' Model 204-4.0 High Intensity LED Sensor System meets all of the anticipated necessary conditions for close proximity robotic sensing in our application: gross motion planning and control in an unconstrained environment. Its 4" range, <0.00008 sq. in. footprint and 250 Hz measurement rate should provide sufficient flexibility for our robotics application, while its accuracy of ± 0.015" despite widely varying target textures, colors, and compositions is an order of magnitude better than we require. However, the system's unexpected ability to maintain this accurate performance even though the target's surface is nearly parallel to the broadcast signal makes this system uniquely suited to the unconstrained environments found in our applications.

The most significant system limitation discovered was its restricted orientation performance for glossy black surfaces, i.e. glossy black targets are only visible within about a 30° range. While this limitation may eventually prove to be significant, one must remember typical sonar systems are even more restrictive. The Spectronics systems are the only known non-contact proximity sensors capable of detecting targets which have large angles of incidence.

ACKNOWLEDGMENTS

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