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Using Infrared Sensors and the Phong Illumination Model to Measure Distances

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Abstract

Currently, the viability of infrared (IR) as an accurate means of measuring distance depends on extensive prior knowledge of the surface. More specifically, the manner in which a surface scatters, reflects, and absorbs infrared energy is needed to interpret the sensor output as a distance measure. In order to use IR in an unknown environment, one must determine the surface properties during *robot operation. This paper details a method of determining the properties of a surface, vis-a-vis infrared reflectance, and subsequently calculating the distance to the surface and the relative orientation of the surface using previously acquired sensory data. We present examples of IR distance measures for various surfaces using known environments as well as examples where the prior knowledge has been acquired using sonar sensing. Our results demonstrate that infrared sensors can provide accurate range measurements when used in conjunction with other sensing modalities to fit model parameters during robot operation (i.e. in real-time).*

Keywords: Infrared sensing, mobile robots, range, sensor fusion.

1 Introduction

In order for a robot to work autonomously in an unknown environment, it must detect obstructions within its vicinity. Traditionally, sonar has provided a reliable source of obstacle detection; however, sonar usage is limited due to its wide beam-width, sensitivity to specular surfaces [4], and the inability to discern objects within 0.5m [3]. These deficiencies limit the ability to use sonar while performing tasks at short distances from obstacles, such as wall following and docking. On the other hand, infrared sensors give reliable readings at close ranges (0.0 - 0.6m). However, the current practice is to utilize infrared as a proximity sensor, not for distance measurements as expressed by Sabatini *et. al.*, "no attempt is made to exploit the peak amplitude of the return signal for distance estimation purposes, because of its sensitivity to the reflectance properties of the objects."[8] As a result, infrared is typically only used for binary distinctions, i.e. obstacle or no obstacle.

Here we show that an obstacle's reflectance properties can be determined if the infrared sensors are originally situated at a known distance from the obstacle. Once the reflectance properties are known, the infrared sensor would become an accurate range finder for the surface at small distances. To ascertain this initial distance, one could use a sonar map built using belief [6] or probabilistic methods [2]. We propose that it is possible to combine sonar mapping and infrared to create a complementary system that is able to give reliable distance measurements within 0.0 to the maximum range of sonar.

This paper describes a method that detects the infrared reflectance properties of a surface, and thereafter uses these properties to calculate a distance using sensor readings. The basis of our approach is the Phong Illumination Model [7], which is traditionally used as a shading algorithm in computer graphics routines. This model was chosen because it is able to approximate the reflectance properties of any surface illuminated by a point light source (and IR LEDs are well approximated as a point light source). In addition, the Phong model is easily manipulated to represent the varying degrees of these reflectance properties for different surfaces, and many of the variables associated with the Phong Model are easily determined by the geometry of the system. As a result, the Phong Illumination Model determines the extent of specular and diffuse reflection for a surface and this information

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is then used to interpret IR data into precise distance measurements.

In order to use the Phong model one must have some prior geometric information. Here we use both known geometry (to demonstrate the effectiveness of the model) and then show how the geometry can be obtained from prior sensing (such as sonar). In the following sections we present our model of IR sensing and show how one can fit parameters to the Phong model. We demonstrate the suitability of this model on various surfaces found in our laboratory. Our experiments confirm that, subject to prior geometric information, the infrared sensors can be used to compute accurate distance within the 3-25 cm range. Finally we show how prior maps built using sonar sensing can be utilized to provide the required prior geometric information.

2 Infrared Sensor Properties

The infrared sensors used for this paper consisted of one infrared LED and two corresponding photodiodes. The function of the sensors is to measure the amount of energy reflected by an obstacle from the LED. As a result the signal returned from the sensor is dependent on the energy emitted from the LED and the detectable range of the photo-diode. These limitations caused problems at the upper and lower end of the sensor range. When the sensor was positioned close to an obstacle, within 5cm, and aimed near 90^o from the surface of an obstacle, the photo-diode began to saturate, and was unable to detect any additional reflected energy. In contrast, readings taken at distances above 25cm became indistinguishable due to the lack of energy detected by the photo-diode. Nevertheless, within this range the infrared sensors behaved monotonically with respect to distance. Thus, within the sensory limitations of an infrared sensor, it is possible to utilize the signal for distance estimation.

3 Methodology

The process of using infrared to determine the distance to an obstacle can be broken into three steps. First, the properties of the obstacle are determined (in this step prior geometric information is required). Secondly, a system must find the angle or orientation of the surface relative to the sensor. After collecting this information, the distance to the object can be calculated.

3.1 Determination of Surface Properties

In order to describe a surface, the Phong Model is chosen to provide a simplified description of how electro-magnetic energy (light) interacts with a surface. As light energy hits a surface it is scattered, absorbed, or reflected. Unfortunately, different surfaces scatter, absorb and reflect light in different proportions. A black surface will absorb more light than a white surface, and a shiny surface will reflect more energy than a matte surface. The Phong Model consolidates these effects into four constants: C_0, C_1, C_2, and n. The Phong Equation for intensity of energy, I, reflected from a surface is

$$I = C_0(\vec{\mu_s} \cdot \vec{\mu_n}) + C_1(\vec{\mu_r} \cdot \vec{\mu_v})^n + C_2 \tag{1}$$

where μ_s, μ_n, μ_r, and μ_v, are the light source, surface normal, reflected, and viewing vector, respectively, depicted in Figure (1). In addition, Figure (2) represents a robot emitting infrared energy and the interaction of the energy with a flat surface.

When comparing Figure (1) with Figure (2), one can determine the value of $(\vec{\mu_s} \cdot \vec{\mu_n})$ and $(\vec{\mu_r} \cdot \vec{\mu_v})$. First of all, the angle between the source vector$(\vec{\mu_s})$ and the normal$(\vec{\mu_n})$ of the surface is α. Also, if one assumes that the infrared emitter and receiver are in the same position$(\vec{\mu_v} \approx \vec{\mu_s})$, then the angle between the viewing vector$(\vec{\mu_v})$ and the reflected vector$(\vec{\mu_r})$ is 2α. Consequently, when applied to Figure (2), Equation (1) becomes

$$I = C_0 \cos(\alpha) + C_1 \cos^n(2\alpha) + C_2 \tag{2}$$

Furthermore, the energy absorbed by the photodiode is a function of Intensity(I), distance traveled(2ℓ), and the area(A) of the photo-diode.

$$E = \frac{IA}{(2\ell)^2} \tag{3}$$

From Figure (2) ℓ can be expressed in terms of d, α, and the radius of the robot(r).

$$\ell = \frac{d}{\cos(\alpha)} + r\left(\frac{1}{\cos(\alpha)} - 1\right) \tag{4}$$

By combining equations (2), (3), and (4) with the assumption that $C_2 = 0$, $n = 1$ and A is constant, the energy absorbed by the sensor is simplified to

$$E = \frac{C_0 \cos(\alpha) + C_1 \cos(2\alpha)}{\left[\frac{d}{\cos(\alpha)} + r\left(\frac{1}{\cos(\alpha)} - 1\right)\right]^2} \tag{5}$$

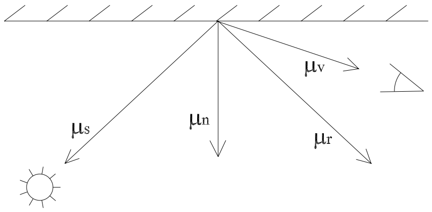

Figure 1: Phong Model

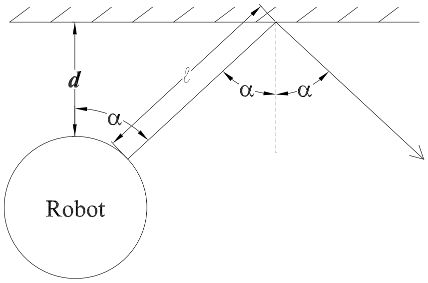

Figure 2: Diagram of Robot emitting an infrared signal

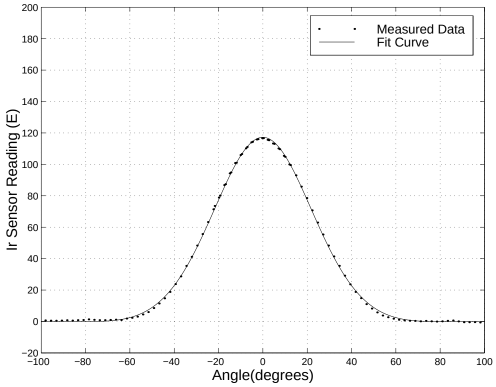

Figure 3: Equation (5) is fit to data collected from a white wall 15cm from the robot. The data was compiled from one sensor while the robot rotated 360^o.

Finally, C_0 and C_1 in Equation (5) describe the infrared characteristics of an obstacle. One can determine these values by examining infrared readings at known distances(d), and angles(α). By applying this data to Equation (5), a least squares fit is used to determine C_0 and C_1 (Figure 3). Once C_0 and C_1 are known, E can be projected for a given angle and distance using Equation (5) (Figure 4).

3.2 Determining the Angle of a Surface

To simplify calculating the surface properties and the distance of an obstacle, one must first ascertain the relative angle of each sensor to the surface. We start by examining an array of IR sensors positioned around the cylindrical frame of our robot. The readings from this configuration will result in a plot similar to Figure (5). In Figure (5), the spike occurs where the direction of the IR signal corresponds to the surface normal ($\alpha = 0$). By approximating where the maximum reading occurs, one can estimate where $\alpha = 0$. A quadratic does provide a good approximation of where the maximum occurs, especially when the closest sensors are saturated and unusable, such as in Figure (6). Therefore, a quadratic fit of the closest infrared sensor readings to the obstacle provides a good approximation of the orientation of the surface.

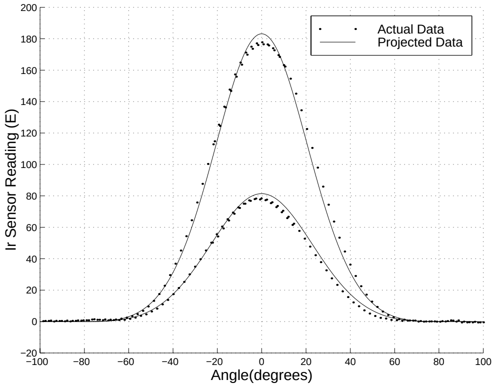

Figure 4: Projected and actual data for an infrared sensor at 12cm and 18cm

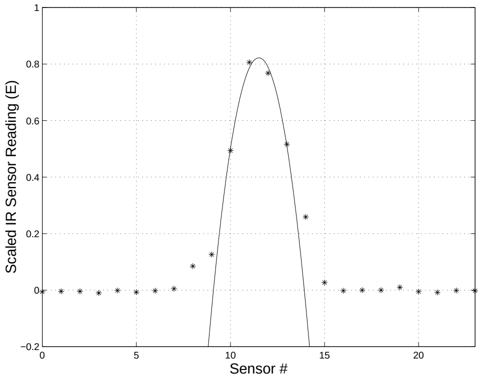

Figure 5: The quadratic fit of the data gives a good approximation of where $\alpha = 0$.

3.3 Calculating the Distance to an Object

After determining the properties of a surface, calculating the distance becomes simple. To translate an infrared reading into a distance, one must first solve

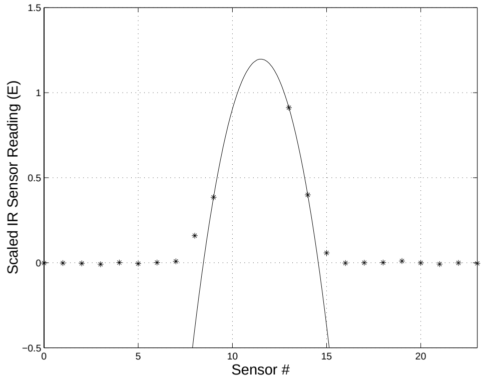

Figure 6: The quadratic fit still provides a good approximation of the orientation of the surface even though sensors 10, 11, and 12 are saturated.

Equation (5) for d.

$$d = r\left(\cos(\alpha) - 1\right) + \cos(\alpha)\sqrt{\frac{C_0\cos(\alpha) + C_1\cos(2\alpha)}{E}} \tag{6}$$

Consequently, given C_0, C_1, E, and the angle (α) of one sensor, d is easily calculated.

4 Experimental Results

To test this theory, we used a Real World Interface B21 robot, with 24 infrared sensors positioned around the outside of its cylindrical frame (see figure 8). The robot was placed 10cm away from a brown metal desk, where it returned readings from all of the sensors. Using the procedure outlined in Section 3.2, the angular position of all the sensors(α) was computed relative to the normal of the surface. We then used the readings of the four closest sensors and Equation (5) to find C_0 and C_1. Finally, we repositioned the robot and calculated the distance between the robot and the wall by using Equation (6) and the closest sensor. Figure (7) compares these calculated distances and the measured distances between 5cm and 23cm. Above 23cm, the infrared readings were too small, yielding inaccurate results. When the robot was positioned closer than 10cm, the closest sensor began to saturate causing the second closest sensor to be used. This raised the error to 0.5-0.6cm. On the other hand, all of the calculated distances between 10cm and 16cm were very accurate. The greatest error in this range was only 0.2cm. In addition, this procedure worked with similar accuracy with many other flat surfaces, including painted drywall, and finished, unfinished, and painted wood.

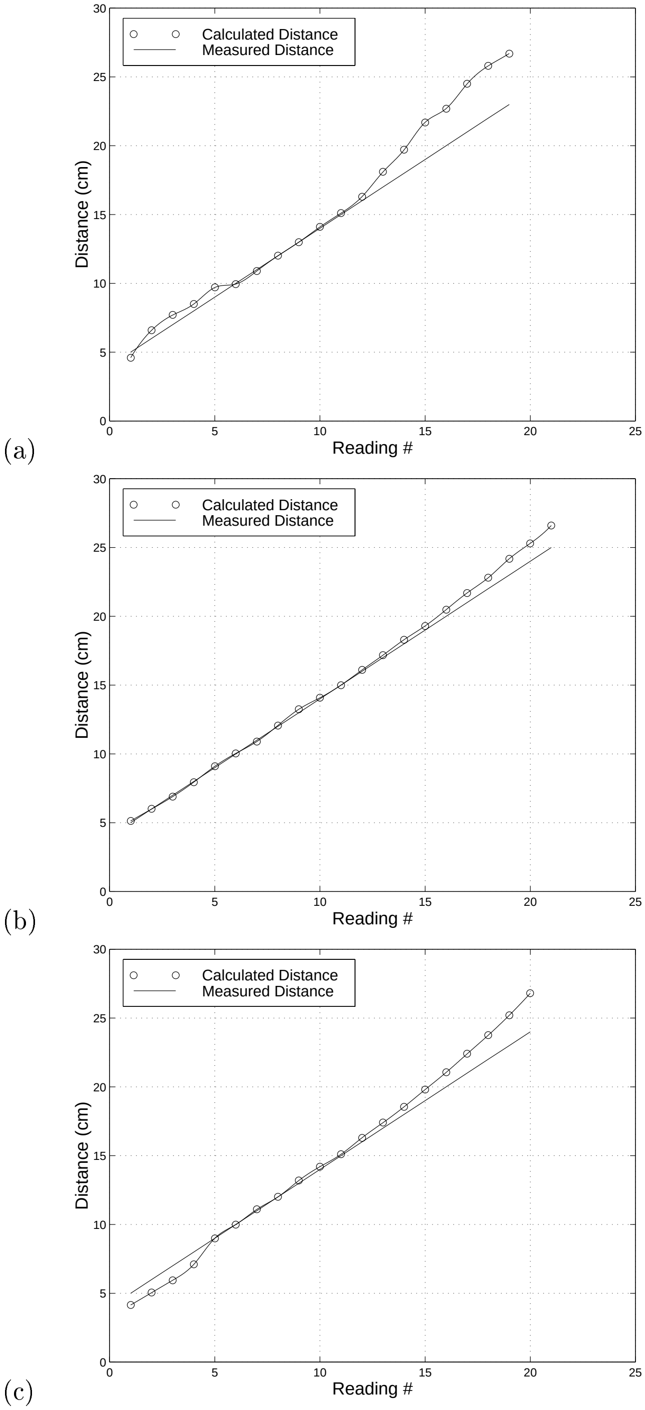

Figure 7: Comparison of Calculated vs. Measured distance with (a) a Brown Metal Desk, (b) White Painted Drywall surface and (c) Unfinished Wood surface.

Table (1) shows C_0 and C_1 calculated for different surfaces. As expected, the shinier surfaces(metal desk) reflected the infrared specularly, resulting in a

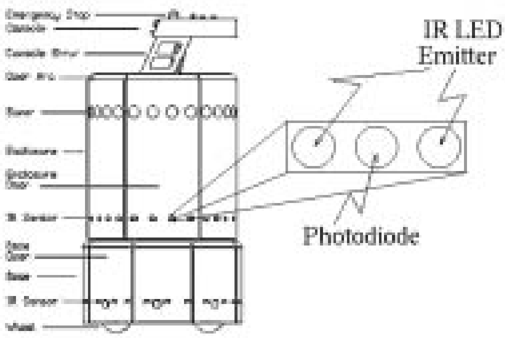

Figure 8: Schematic of our RWI B21 mobile robot with IR sensors used in experiments

	C_0 *Diffuse*	C_1 *Specular*
White Painted Drywall	193.83	8.17
White Painted Wood	183.21	46.91
Unfinished Wood	101.24	93.88
Finished Wood	50.89	100.88
Brown Metal Desk	0.00	106.88

Table 1: Model coefficients which represent the reflective properties of various surfaces

high C_1. In contrast, rough surfaces(painted drywall) scattered most of the infrared energy causing a high C_0. As a result, the Phong Illumination Model does provide a qualitatively accurate description of the surfaces tested.

4.1 Experiments with Prior Maps

In order to fit the parameters to the Phong Model, the distance to obstacles must be known *a priori*. In the previous sections we positioned the robot manually. To utilize the Phong Model in unstructured or unknown environments, the distances to obstacles must come from other sensing modalities. Here we demonstrate that maps built from sonar can provide the required geometric (distance) information. We used the method described by Pagac *et. al* [6] to build a map of the environment from sonar sensors. An example belief map occupancy grid is shown in figure 9 in grey-scale. Dark regions indicate high belief that the region is occupied. We used a map with resolution of 1 cm by 1cm. For obstacles in front of the robot, a line was fit to the computed map. Using the belief map, the robot estimated its position at 15 cm from the obstacle (the actual distance was 15.3 cm). The estimated distance and orientation of the (presumed flat) obstacle was used to fit the surface properties C_0 and C_1 described in section 3.1. Using these parameters, the robot could then utilize IR measurements to accurately measure distance to obstacles. Figure 10 shows the calculated distances to a white painted drywall surface obtained from the IR sensors after using the sonar map to calibrate the IR. Comparing figures 10 with figure 7(b) shows that the accuracy is similar to our previous experiments (where the exact robot distance to the obstacle was measured).

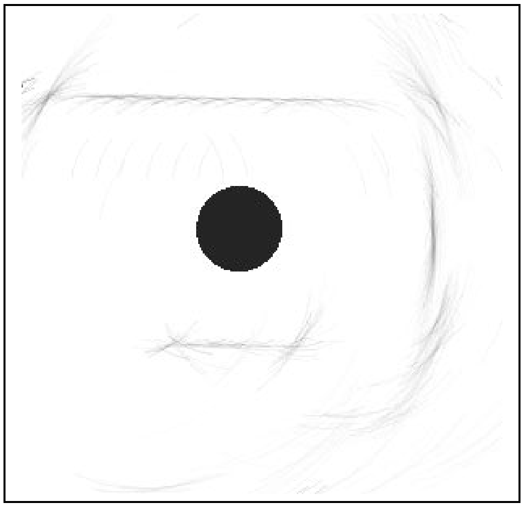

Figure 9: Belief map for room occupancy obtained using sonar data.

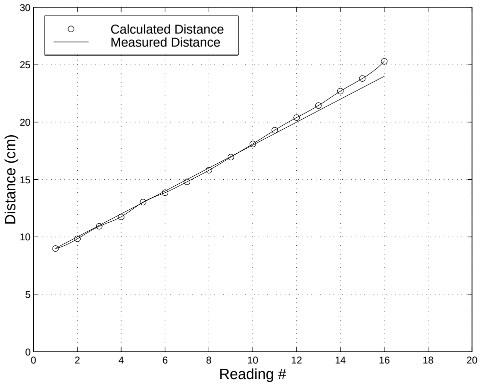

Figure 10: Calculated distance to painted drywall surface obtained using sonar map to provide the geometric information required to estimate the Phong Model parameters

At close distances (less than 10 cm), the sonar sensors cannot be used for range measurement however, with model fitting, IR can provide precise distances, enabling the robot to follow the wall (and not having to rely on error-prone dead-reckoning [1]).

5 Discussion

It has been shown that the Phong Illumination model is a good description of the interaction of an infrared sensor with an obstacle. In our procedure, the Phong Model was first used to determine the properties of a surface encoded as model coefficients C_0 and C_1. Once C_0 and C_1 were found, we were able to calculate the distance and angle of a flat surface. This method proved to be an accurate means of using infrared as a range-finder.

To further improve infrared sensors, future research will examine the effects of n in Equation (1) In the Equation (1), n is used to describe the specular falloff of a reflection. For example, a highly reflective surface corresponds to a high n. For simplicity, we assumed that n in Equation (1) was equal to one. This allowed for a linear least squares fit of C_0 and C_1. Although this assumption did provide good results, a nonlinear fit to find C_0, C_1, and n might provide a more complete model.

Our primary goal is the eventual fusion of sonar, infrared and other sensors for mobile robots. We have shown preliminary results on using sonar to provide the seed distances needed in Section (3.1) to determine the model coefficients (surface properties) of an obstacle. This would allow for a complete sensor that would mesh the long range of sonar with the accurate close proximity(0.0-0.6m) measurements of infrared. While we have demonstrated that sonar and infrared can be combined in this fashion, we are further exploring issues on the frequency of "on-line" calibration required. As the robot performs a task, such as wall following, the surface may change (for example a hallway has both wooden doors and painted drywall). Detecting changes between the measured distances and the predicted distance (based on the prior map) will indicate necessary re-calibrations. Current investigations are exploring these and other issues.

The simplicity of the model presented, and the accuracy of the resulting distance measures indicates that infrared can be utilized as a range-finder rather than simply a proximity sensor.

Figure 11: Wisbot, a Real World Interface B21 mobile robot used for our experiments.

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