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Adaptive Phototransistor Sensor for Line Finding

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Abstract

Line finding is used by wheeled mobile robot for localization. A phototransistor array was designed to detect the line position relative to the robot. This sensor is composed of six phototransistors to detect the position of line on the floor relative to the wheeled mobile robot. Because the ambience may change with time and the floor colour may be different from one location to another, an adaptive scheme has been designed to find the line on the floor. This proposed scheme consists of three parts; modulation and demodulation, threshold recognition with k-means clustering, and line finding with fuzzy logic. Modulation and demodulation technique is used to tackle the problem of different ambience in the surrounding. K-means clustering is used to recognize the contrast in the colour of line and floor while fuzzy logic is used to find the line relative to the sensor. Experiments were conducted in a microcontroller and it was found out that this scheme can find the line on the floor with minimum error.

Keywords: Phototransistor; line finding; discrete Fourier transform; k-means clustering; fuzzy logic.

1. Introduction

Line finding algorithm is useful for many applications, and one of the examples is wheeled mobile robot localization. The algorithm finds the position of line relative to the robot so the robot has a sense of direction and locality. Line finding is particularly useful in navigation because it provides absolute localization. As compared to dead-reckoning localization, line finding provided reading that will not deviate from actual value as the wheeled mobile robot navigates.

There are many devices that have been used for line finding. In general, cameras and phototransistor array are used. Camera can give useful information about the surrounding and the direction of the wheeled mobile robot is moving in. As example, project by Ismail et al [1] and project by Dupuis and Parizeau [2] incorporate vision in their robots to perform line following. Other authors like Kahn [3] and Bonci [4] focused on fast and effective line finding algorithms. Even though camera provides this useful information, the computational effort is high. Besides, high quality camera might be costly.

On the contrary, phototransistor array is generally used to find a line on the floor. Typical lines are bright colour strips placed on dark coloured surface or vice versa. Application for this line can be found in robotic competitions [5], education [6,7], or automated guided vehicles [8,9].

When dealing with line finding algorithm, there are several issues to be tackled including ambience, reading thresholds and line position search. Ambience is a problem when dealing with image processing either using cameras or phototransistor array. Different ambience setting will give different reading on the sensor. This can be solved by normalizing the histogram

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in a camera image [1]. However this method cannot work well in phototransistor arrays because the limited information available and noise in the reading signals.

Reading thresholds are particularly important for phototransistor array type of line finding sensor. This is due to different colour and brightness of the navigation floor space of the mobile robot. With similarity to the ambience problem, the variation in colour, brightness, and contrast will give different reading in the line finding sensors.

Line position search is the main component of line finding algorithm. The line has to be detected on the sensor for the mobile robot to localize. The line position can be represented as straight line on a Cartesian coordinate in a camera image. In phototransistor array, the line position can be represented as a single reading in a single dimensional space.

Phototransistor array that composed of six phototransistors was used in this project. The three mentioned issues are tackled with three different methods. First of all, the phototransistor signals are passed through the discrete Fourier transform algorithm for peak detection. This algorithm will solve the difference in ambience problem. Thereafter, all the signals from the array are collected, and one dimensional k-mean clustering is applied to search for the thresholds. Finally, fuzzy logic is used to search for the line position relative to the sensor. The final product of this experiment is an adaptive line finder that is suitable in different ambience settings and robust against environment changes.

2. Adaptive Phototransistor Sensor System

This section describes the methodologies used to solve the three problems mentioned when dealing with phototransistor array line finding operation. Discrete Fourier transform (DFT) is used to solve the difference in ambience setting, k-means clustering is used to search for the thresholds in the readings, and fuzzy logic is used to find the line position relative to the phototransistor array.

Discrete Fourier transform is used to find the frequency spectrum in discrete form from a given discrete signal [10]. In this project, this algorithm is used to find a specific amplitude from a series of discrete phototransistor signal.

K-means clustering is an algorithm used to find the means for *k* cluster in a pool of data in *n* dimensional space [11]. In this project, a two cluster algorithm is used to find the means of clusters in a single dimensional space.

Fuzzy logic is a linguistic reasoning tool used for decision making based on analog values [12]. For this project, a fuzzy logic with six inputs from the phototransistors will be used to find one output, which is the line position.

2.1. Discrete Fourier Transform (DFT) for Phototransistor Signal Processing

Phototransistors are used as transducer from light to voltage in this project. Light emitting diodes (LED) are also used along with the phototransistors for illumination, where the light from LED will be reflected from the floor to the phototransistor. There are six pairs of LED and phototransistor used in this project and they are arranged in a straight line.

The voltage reading from the phototransistor can be used directly, but this reading might be affected by different ambience settings. As example, brighter ambience might give higher voltage reading while dimmer ambience might give lower voltage reading. In other words, there is a d.c. offset in the voltage reading, which depends on the ambience of the surrounding.

To solve this problem, modulation was done by transmitting a light signal through the LED with a specific carrier frequency. Thereafter, the voltage signal from the phototransistor was demodulated by finding the amplitude of the signal on the carrier frequency. A method similar to this is coined in [9] but the method is implemented using electronic circuits. Method implemented using circuitry are noisy and hard to implement.

Table 1. Listing for DFT algorithm

Step 1: Light up the LED
Step 2: Sample the phototransistor
Step 3: Wait until $T_c/2$
Step 4: Turn off the LED
Step 5: Sample the phototransistor
Step 6: Wait until T_c
Step 7: Repeat from Step 1 for the number of samples required
Step 8: Apply the DFT formula to obtain the brightness reading

This proposed method was performed by lighting up the LED with a square-wave signal of frequency f_c. Then, the voltage from the phototransistor was sampled using a frequency double of f_c. Finally, DFT equation (1) was applied to find the amplitude of the signal on the frequency f_c [13].

$$X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-i2\pi \frac{k}{N} n} \tag{1}$$

where x_n is the series of voltage signals from the phototransistor and X_k is the amplitude of signal on the frequency f_c. N is the total number of samples per DFT operation and $k = N/2$ is used. Put differently, if the carrier signal is f_c, the voltage sampling frequency should be double of f_c. This also implies, the DFT equation is performed at the specific frequency of f_c, if $k = N/2$ is used. Because only the specific frequency is needed, the DFT equation can be simplified to equation in (2). The algorithm listing is in Table 1.

$$\begin{aligned} X_{N/2} &= \sum_{n=0}^{N-1} x_n \cdot e^{-i\pi n} \\ &= \sum_{n=0}^{N-1} x_n (\cos(\pi n) - i\sin(\pi n)) \\ &= x_0 - x_1 + x_2 - x_3 \cdots + x_{N-2} - x_{N-1}, N \in even \end{aligned} \tag{2}$$

2.2. K-Means Clustering for Threshold Search

The phototransistor array is used to locate a line position on the floor where the colour of the floor might not be consistent throughout the navigation space of the mobile robot. This implies the bright and dark readings might be different from one place to another. Therefore, the reading thresholds need to be calibrated in real time and this is performed using the single dimensional k-means clustering [11].

Ten readings from each phototransistor were obtained from the DFT operation for clustering. This means there is a pool of 60 reading elements for the clustering operation. Two clusters were obtained from the pool of data using the k-means algorithm. The result of the algorithm is two thresholds value: bright threshold (or maximum threshold) and dim threshold (or minimum threshold). Using these two thresholds, the line finding operation can be preceded. Table 2 shows the algorithm listing.

Table 2. Listing for k-means clustering algorithm

Step 1: Initialize with two threshold values, MAX_THRES and MIN_THRES, with MAX_VALUE and 0.
Step 2: Obtain average, AVE, of MAX_THRES and MIN_THRES
Step 3: Reset the value of MAX_THRES and MIN_THRES
Step 4: Iterate through all readings. If the value is larger than AVE, add to MAX_THRES, else add it to MIN_THRES.
Step 5: Find the mean of MAX_THRES and MIN_THRES
Step 6: Repeat from Step 2 until consistent value of MAX_THRES and MIN_THRES were obtained.

2.3. Fuzzy Logic for Line Finding Operation

Fuzzy inference system [12] is used for the line finding operation because it provides a crisp output value from crisp input value. In other words, the discrete signals from the phototransistors are passed through the fuzzy inference system to obtain a discrete line position value. The fuzzy inference system consists of four parts: fuzzification, rule base, inferencing and defuzzification.

There are six inputs to the fuzzy inference system, noted with $u_i, i = [0,5]$. Each input has two membership functions, noted with LIGHT_MEMBER and DARK_MEMBER. Trapezoidal function is used to obtain the degree of truth for each input. This is depicted in Fig. 1. The thresholds values are obtained from the clustering operation.

Inferencing is done based on the rule base and the degree of truth for each input members. Considering the number of inputs and number of members for each input, there are 2^6 rules to be established, which is quite a large number. Therefore, only certain rules that are logical are established. Assuming only one line on the floor, 13 rules are established as shown in table 3.

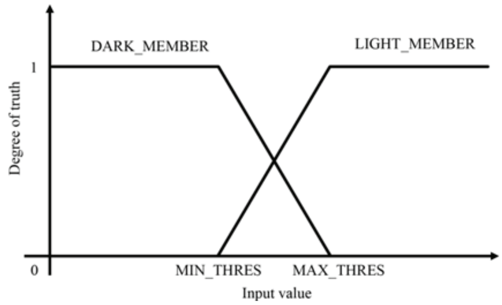

Fig. 1. Input membership functions for each phototransistors

Table 3. Rule base for the line finding algorithm

Rules	If Input 0	And if Input 1	And if Input 2	And if Input 3	And if Input 4	And if Input 5	Then Conclusion
1	DM = High	DM = High	DM = High	DM = High	DM = High	DM = High	OM 0 = High
2	**LM = High**	DM = High	DM = High	DM = High	DM = High	DM = High	OM 1 = High
3	**LM = High**	**LM = High**	DM = High	DM = High	DM = High	DM = High	OM 2 = High
4	DM = High	**LM = High**	DM = High	DM = High	DM = High	DM = High	OM 3 = High
5	DM = High	**LM = High**	**LM = High**	DM = High	DM = High	DM = High	OM 4 = High
6	DM = High	DM = High	**LM = High**	DM = High	DM = High	DM = High	OM 5 = High
7	DM = High	DM = High	**LM = High**	**LM = High**	DM = High	DM = High	OM 6 = High
8	DM = High	DM = High	DM = High	**LM = High**	DM = High	DM = High	OM 7 = High
9	DM = High	DM = High	DM = High	**LM = High**	**LM = High**	DM = High	OM 8 = High
10	DM = High	DM = High	DM = High	DM = High	**LM = High**	DM = High	OM 9 = High
11	DM = High	DM = High	DM = High	DM = High	**LM = High**	**LM = High**	OM 10 = High
12	DM = High	DM = High	DM = High	DM = High	DM = High	**LM = High**	OM 11 = High
13	DM = High	DM = High	DM = High	DM = High	DM = High	DM = High	OM 12 = High

* DM = DARK_MEMBER, LM = LIGHT_MEMBER, OM = OUTPUT_MEMBER

From Table 3, notice that the premise for the first and the last rules are the same but give out different conclusion. This is the situation where the line is out of the range of detection. Therefore, a memory is used to store the previous location of the line relative to the sensor either being left or right. If there is a situation where the first or the last premise being activated, the memory will decide which premise is valid and activate the corresponding conclusion.

Fuzzy logic inference mechanism that is used to determine the conclusion of each premise is MIN function (3), and the implication for each output member is the singleton of each conclusion (4).

$$CONCLUSIONj = MIN(PREMISE0, PREMISE1, \cdots, PREMISEi), i = [0,5], j = [0,12] \quad (3)$$

$$OUTPUT\_MEMBERj = SINGLETON(CONCLUSIONj), j = [0,12] \quad (4)$$

$$y = \{OUTPUT\_MEMBER0, OUTPUT\_MEMBER1, \cdots, OUTPUT\_MEMBERj\}, j = [0,12] \quad (5)$$

Thereafter, defuzzification process is proceeded to find the discrete value of line position, $\hat{y}$. Each output membership (5) is assigned a centroid value, μ_j , ranging from –A to A, and equally spaced. This is depicted in Fig. 2. The formula is given by (6).

$$\hat{y} = \frac{\sum_{j=0}^{12} \mu_j \times OUTPUT\_MEMBERj}{\sum_{j=0}^{12} OUTPUT\_MEMBERj} \tag{6}$$

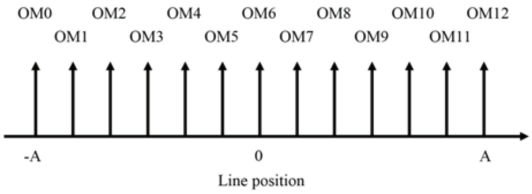

Fig. 2. Output membership for defuzzification

3. Experiment Setup

These algorithms were implemented in a dsPIC30F4012 microcontroller from Microchip Technology. The microcontroller and the phototransistors were fabricated on a printed circuit board, and experiments were conducted to validate the algorithms. The range of phototransistor signal is 0 to 5V and the phototransistor is a NPN type. The circuit board is depicted in Fig. 3(a).

First of all, the DFT algorithm is tested. Three different ambience setting is used: dark, where the lights in the room are switched off; normal, where the lights in the room are switched on; and bright, where a torch light was shine upon the floor, which the sensor is reading from. As comparison to normal voltage reading, the data from the analog-to-digital converter (ADC) is logged along with the result from DFT. Two colour of the floor is tested on: green coloured floor and white coloured floor.

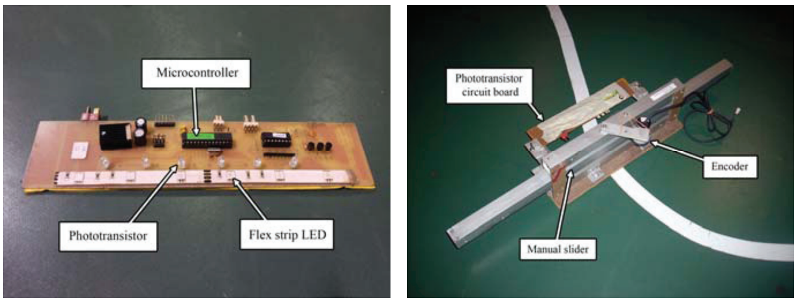

Fig. 3. (a) Phototransistor circuit board, (b) Experiment setup on a manual slider

In the second experiment, the k-means clustering algorithm is tested. The experiment setup in Fig 3(b) is used, where there is a white line present on the floor. The white line is 3cm wide, drawn on a green surface. Data that had been collected from the DFT algorithm are used for the k-means algorithm.

Finally, the fuzzy logic is tested to find the line of the floor. Experiment setup in Fig 3(b) is also used in this experiment. To validate the line position obtained from the microcontroller, it is compared with an encoder. The slider was manually slid left and right, and the line finding algorithm was performed.

4. Results and Discussions

4.1. Result from the Discrete Fourier Transform Algorithm

From the experiment results as shown in Fig. 4(a) and Fig. 4(b), the brightness reading (phototransistor signal) from the DFT are less affected by the ambience setting as compared to the direct ADC reading. As seen from both figures, the ADC readings are almost similar in dark and bright environment but when exposed to a bright ambience, the reading changed. It is noted that the reading from the phototransistor is inversely proportional with the brightness. This is expected because the phototransistor used is a NPN type. On the contrary, the resulted reading from the DFT algorithm is proportional with the brightness. This is because the amplitude of the signal on the carrier frequency is higher in bright surface compared to dark surface.

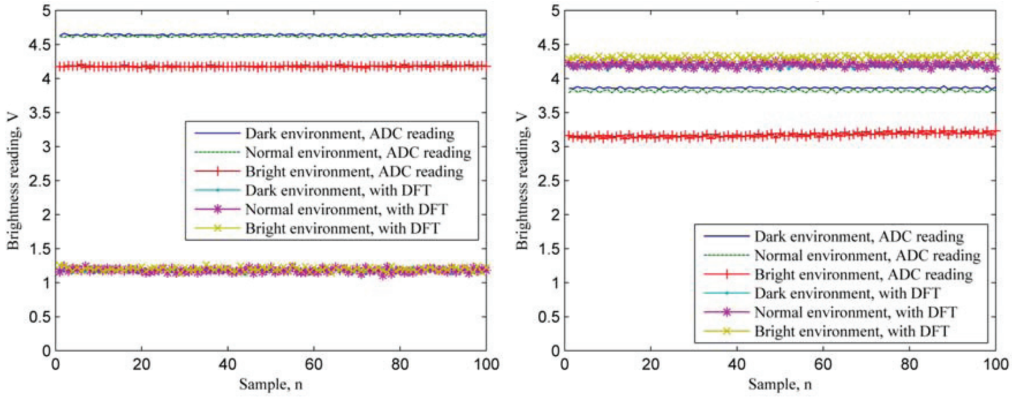

Fig. 4. Data collection on (a) green surface and (b) white surface

4.2. Result from the K-Means Clustering Algorithm

From the result as shown in Fig. 5, there are two clusters collected from all the phototransistors. The MAX_THRES mean is the average of the upper cluster while the MIN_THRES is the average of the lower cluster. The upper cluster is actually the data from the phototransistors that is situated on the bright line, while the lower cluster is the data from the phototransistors that is situated on the dark surface. These two thresholds value will be used in in the fuzzy logic algorithm for the line finding operation.

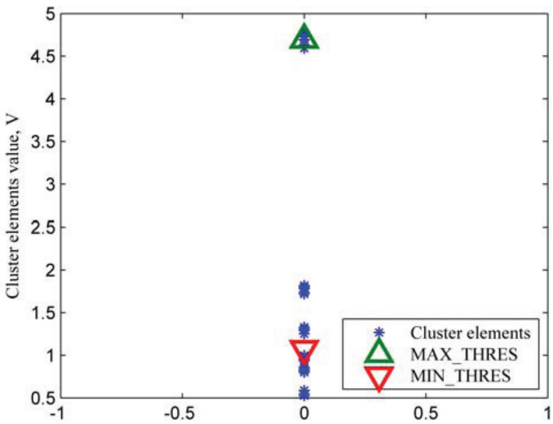

Fig. 5. Elements in the cluster and the calculated threshold values

4.3. Result from the Fuzzy Logic Line Finding Algorithm

The result is shown in Fig. 6, where the line position obtained from the fuzzy logic is compared to an encoder. It was shown that the fuzzy logic algorithm is effective in finding the line position relative to the phototransistor circuit board. The value of *A* from Section 2.3 is 6.5 cm which correspond to length from the first phototransistor to the last transistor on the circuit board. This means the overall range is 13 cm. The mean of absolute error is 0.2cm or 1.59% from overall range.

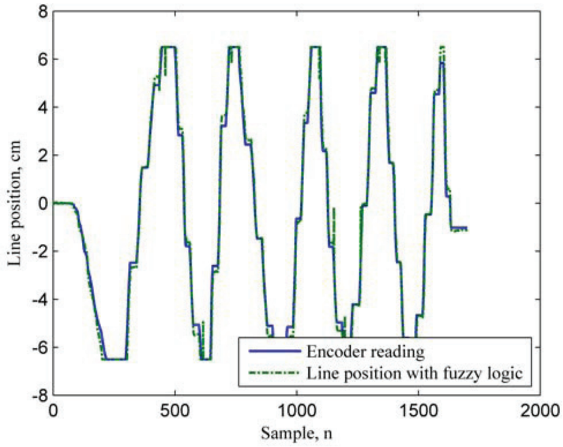

Fig. 6. Comparison of line position from encoder and fuzzy logic algorithm

5. Conclusion

An adaptive scheme to find a line on the floor using phototransistors have been designed and tested. The scheme is divided into three algorithms, namely the DFT, k-means and fuzzy logic. These three algorithms are used to solve the difference in ambience setting, to find the thresholds in reading and to find the line position relative to the sensor. Experiments were conducted to validate the effectiveness of this line finding algorithm and the result shows the mean of absolute error of line can goes as low as 1.59% of total range, which is a good result. Future works involves the usage of other methods for line finding as comparison to the current method.

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