An intelligent line-following robot project for introductory robot courses

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ABSTRACT: Line-following robots are very popular with technical university and vocational high-school students in Taiwan. Therefore, these projects are quite helpful in motivating students to learn actively the implementation skills for intelligent mobile robots. The line-following robot devised in this article for educational purposes includes not only accurate line detection algorithms with analog outputs of reflective optical sensors, but also home-made encoders, which help record all information about the racing track. The firmware can then plan profiles for the fastest run. The integration of the software control algorithms and hardware circuits make it a suitable teaching aid for introductory autonomous mobile robot courses. The devised robot won first prize in several national contests for line-following robots, which shows its superiority of implementation.

INTRODUCTION

Learning by doing is a very effective idea for students to acquire knowledge, if they are well motivated. It was found that students will be willing to do tedious research work to solve practical problems when these problems are related to an interesting and competitive contest [1][2]. Racing contests of line-following robots are examples [1][3-5]. Line-following robots are self-operating robots that move along a line on the floor. Recently, the Fortune Institute of Technology held six line-following robot racing contests to encourage students from the technological and vocational education system in Taiwan to show their creativity and techniques [3]. It is a very successful contest not only because of the high prize, but also in attracting senior high school students to join the contest. The Taiwan micromouse and intelligent robot contest even included the line-following robot racing contest as a major event last year [5]. The rules, which are similar to those in Japan [4], encourage line-following robot contestants to memorise what the racing track is like by providing hints along the line whenever the curvature is changed. The contestants, therefore, can plan the speed command profiles for their motors for straight-line segments and curves.

In addition to the intelligence of judging precisely where the line is, of memorising the racing track patterns and of speed command profile planning for motors, the mechanical parts and design of the line-following robot are also important to reduce the effect of weight transfer and to prevent skidding when making turns at high speeds. According to the experience of the micromouse world champion [6], the turn speed is a decisive factor in robot speed contests. To make a line-following robot with a speed faster than 1m/sec even when it is making turns, the correct prediction of the line position is a key factor.

Unfortunately, algorithms which are able to predict accurate line position depend heavily on the assumption that reflective optical sensors have similar output characteristics. It is also found that the spacing between reflective optical sensors and the distance between the reflective optical sensor and the ground are important factors for line detection algorithms to work accurately. Therefore, calibration of the reflective optical sensor outputs is an important procedure for a fast line-following robot. The calibration procedure described in Chan's Web page uses white paper and a gain value for each reflective optical sensor to adjust the corresponding output value to a pre-specified value [7]. Lee et al use a more complex approach which needs 20% and 80% of grey patterns to determine the calibration parameters [8][9]. Although the approach in References [8] and [9] is effective, it can only be manually performed. Therefore, an automatic calibration procedure, which uses a pulse-width modulation technique to adjust the light emitted from light-emitting diodes and to simulate the reflecting conditions of 20% and 80% of grey surfaces, is proposed in this article to remedy the problem.

The other requirement for line-following robots to run as fast as possible is its ability to memorise what the racing track is like so that the robot can plan the speed command profiles for its motors for straight lines and curves. This is possible

because the rules used in the 5th Taiwan micromouse and intelligent robot contest, and the all Japan robotrace contest both provide hints when the curvature of the racing track changes. Because of the weight transfer effect, the speed on curves should be slower than for straight lines to prevent skidding [10]. Therefore, the line-following robot should not only differentiate curves from straight lines, but also know the lengths of all the straight line segments. This is why the line-following robot described in this article is equipped with a quadrature encoder. How the encoder is designed and the algorithm used to calculate the lengths of all the straight line segments are also discussed in this article and it was experimentally verified as also reported in this article. Although the robot was developed mainly for both national and international line-following robot contests, the integration of the software control algorithms and the hardware circuits make it a very suitable teaching aid for introductory autonomous robot courses.

OVERVIEW OF THE INTELLIGENT LINE-FOLLOWING ROBOT

The prototype intelligent line-following robot described in this article, the block diagram of which is shown in Figure 1, is a single board computer and costs about NTD2,000. The robot, used for contests and laboratory exercises, consists of a microcontroller dsPIC30F6011, dual H-bridge dc-motor drivers, an RS232 port to communicate with a PC, an LCD display for debugging, an in-system programming (ISP) port for downloading programs from a PC to the 48K byte flash memory, 9 A/D ports for accessing the sound and reflective optical sensor circuit signals and an encoder wheel (Figure 1). The necessary integrated development environment and C-language compiler for the robot can be freely downloaded from the Microchip Inc. Web site.
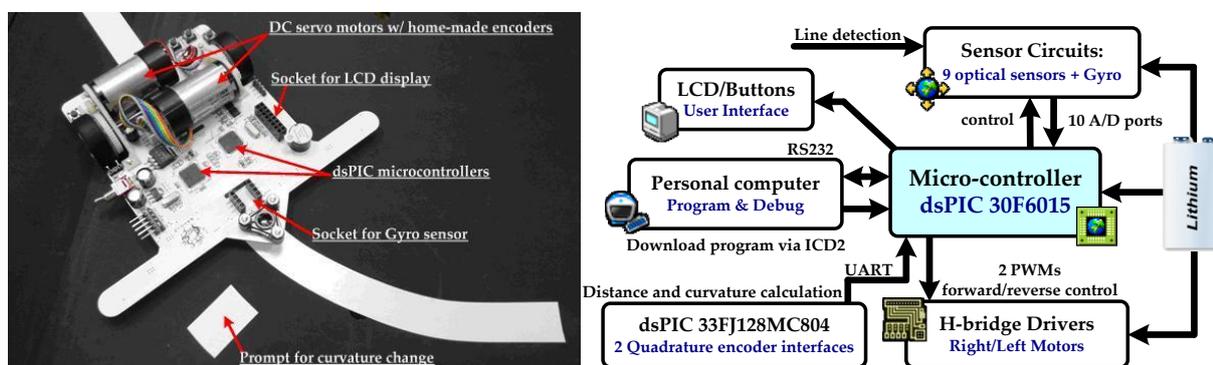
Figure 1: The proposed line-following robot and its corresponding block diagram.

AUTOMATIC CALIBRATION OF REFLECTIVE OPTICAL SENSOR OUTPUTS

To detect the line in the racing track, most people use two or more reflective optical sensors [11][12], and the outputs of these sensors are fed to comparators with predefined threshold trigger values to get the corresponding digital information. Although this approach works fine in detecting the line, the analog information about the reflection rate of the floor, which is related to whether or not the sensor is right on the line, is lost. As can be seen in Reference [13], the reflective collector current of the circuit in Figure 2 can give users the information about how far the reflective optical sensor is from the line. Therefore, the analog output voltage at the collector would become larger and larger as the reflective optical sensor moves away from the line when the floor is black and the line is white. This is the main idea used in Reference [7].
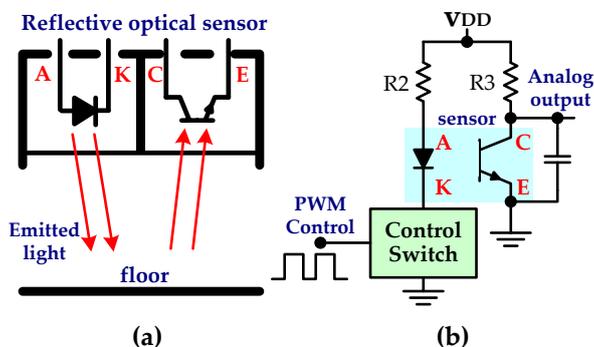
Figure 2: a) The working principle of reflective optical sensors; b) The application circuit.

Unfortunately, the analog outputs for different sensors working under the same conditions vary a lot even if their part numbers are the same. This is why calibration is necessary for those reflective optical sensors installed on the line-following robot. Chan uses gain parameters for each reflective optical sensor such that the analog output values can be adjusted to be the same when white floor is used for calibration [7]. Although it is a relatively simple approach and can be done automatically, it adjusts only the largest analog output values. Lee et al proposed a different approach [8][9].

They tried to fix the analog outputs corresponding to 20% and 80% of grey floor to the same level for all reflective optical sensors. Although this approach is effective in adjusting the sensor analog output values to similar levels under the same working conditions, it would take users quite some time to finish the entire calibration process. An automatic calibration procedure based on the result in References [8] and [9] and pulse-width-modulation (PWM) technique, therefore, was devised to remedy this problem.

Assume that the floor is white. The duty ratio of the PWM control signal shown in Figure 2b is set to be 20% and 80% such that the light energy emitted from the diode of CNY70 would be 20% and 80% of that when the PWM control signal is kept high and the control switch is turned on. This is because the light energy emitted from the diode is proportional to the input energy to the diode, and the forward voltage drop is almost constant throughout the operation range (20mA-100mA) [13]. Therefore, the condition in which one uses full-scale emitted light energy on a 20% grey floor and the other condition in which one uses 20% of emitted light energy on a white floor would have similar analog output voltages in Figure 2b. This is the main idea of the proposed automatic calibration procedure in this article. Let the reflective optical sensors be arranged along a line with equal space between each other. The length of the space can be determined by how far away the sensor is from the line such that the analog value would drop to 50% of its maximum value. The experimental result is shown in Figure 3, in which the line width is 19mm and the value for the space between two consecutive optical sensors is chosen to be 12.5mm.

The values in Figure 3 show that the seven reflective optical sensors actually do not give identical outputs even if the test conditions are the same. The calibration procedure tries to map the output values of each reflective optical sensor with respect to 20% and 80% of grey to the same maximum and minimum values using the following formula:

$$y_{jo} = y_{min} + \frac{y_{max} - y_{min}}{x_{max,i} - x_{min,i}} (x_{ji} - x_{min,i}) , \tag{1}$$

where $x_{max,i}$, $x_{min,i}$, are the maximum and minimum values of the ith reflective optical sensor outputs; y_{max}, y_{min}, are the predefined maximum and minimum values for all reflective optical sensor outputs; x_{ji} is the jth output value for the ith reflective optical sensor, and y_{jo} is the normalised output value for x_{ji}. It can be seen in Figure 3 that the output values of different reflective optical sensors are quite similar to one another after the calibration using Equation (1). Once the calibration procedure is done, the output values of these seven reflective optical sensors are ready to be used in estimating the line position.
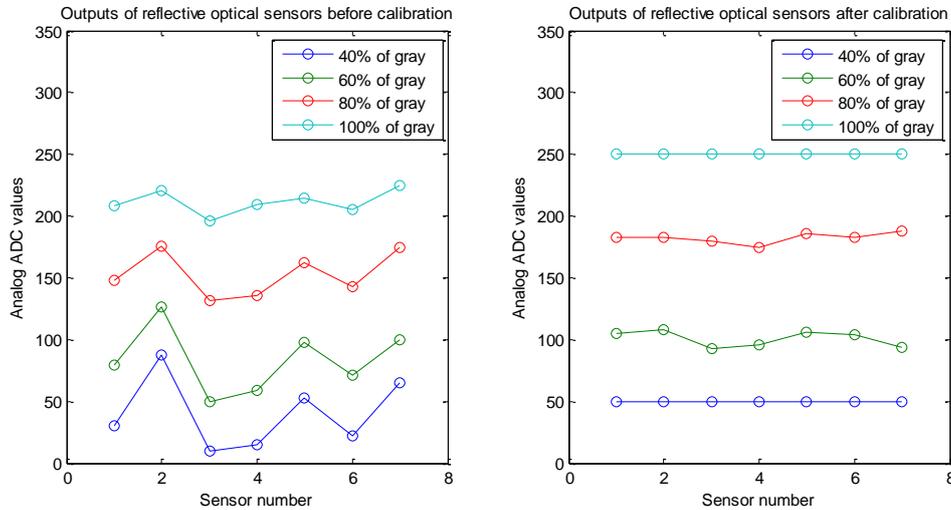
Figure 3: The reflective optical sensor outputs for different grey scales before (left) and after calibration (right).

LINE DETECTION ALGORITHMS

After the calibration procedure, the line position can be calculated based on the adjusted analog output values from the corresponding reflective optical sensor circuits. Various ways are described and experimentally compared in the following. Assume that the line to be followed is black and the floor is white, and there are seven reflective optical sensors installed on the line-following robot. The ideas described below are applicable even if the line to be followed is white and the floor is black.

Line Detection via Quadratic Interpolation

Let the coordinate of the left most sensor be - 3, and the distance between two consecutive sensors be 1. The output of the reflective optical sensor circuit in Figure 4a is higher when the sensor is closer to the black line. Therefore, one can

always find 3 consecutive sensors with higher output readings than the other 4 sensors as shown in Figure 4a. Assume that the coordinate of these 3 sensors are x_1, x_1+1, and x_1+2, and the true shape of the sensor output values in the range of $[x_1, x_1+2]$ can be approximated by a quadratic curve. One can then find the following relationships between the coordinate of the sensors and the output values:

$$y_1 = ax_1^2 + bx_1 + c, \; y_2 = a(x_1+1)^2 + b(x_1+1) + c, \; y_3 = a(x_1+2)^2 + b(x_1+2) + c. \tag{2}$$

The coordinate value at which the output value of the quadratic curve is the maximum is considered as the true position of the line. By using the basic calculus, one would know that the coordinate value is:

$$x = -\frac{b}{2a}, \text{ and } a = \frac{y_1 + y_3 - 2y_2}{2}, \; b = y_2 - y_1 - 2ax_1 - a. \tag{3}$$

It is assumed that the coordinate for the center position of the line-following robot is 0. Therefore, the error e between the line position and the center position of the robot is $e = 0 - x = -x$.

Line Detection via Weighted Average

This technique is the commonly used in defuzzification procedures of fuzzy systems [14]. It can also be viewed as finding the center of mass [15]. Suppose that the coordinate of the 7 reflective optical sensors are x_0, x_1, x_2, x_3, x_4, x_5, x_6, respectively, and the corresponding analog output values are y_0, y_1, y_2, y_3, y_4, y_5, y_6, as shown in Figure 4b. The estimated line position can then be calculated by the following weighted average formula:

$$x = \frac{\sum_{i=0}^{7} x_i y_i}{\sum_{i=0}^{7} y_i} = \frac{3(y_6 - y_0) + 2(y_5 - y_1) + (y_4 - y_2)}{\sum_{i=0}^{7} y_i}. \tag{4}$$
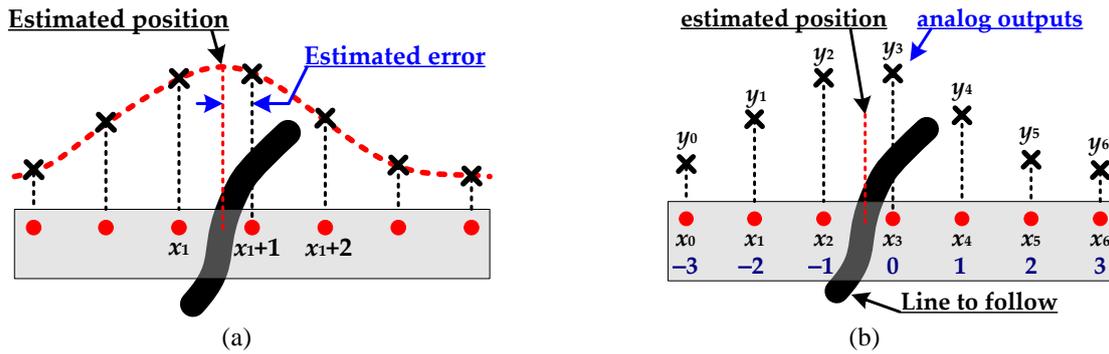
Figure 4: The line detection algorithm via a) quadratic interpolation, and b) weighted average.

Experimental Verifications and Comparisons of Line Detection Algorithms

To verify the correctness and effectiveness of these line detection algorithms, a linear platform was constructed using a desktop inject printer, as shown in Figure 5.
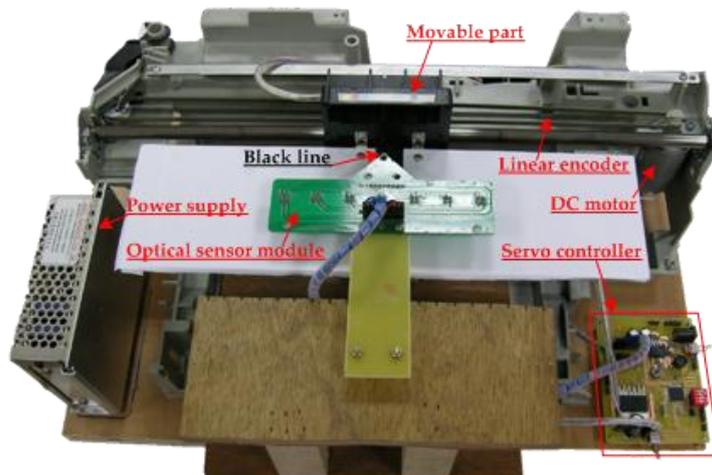
Figure 5: The linear platform devised to verify the correctness and effectiveness of the line detection algorithms.

The resolution of the linear platform is 0.1mm/pulse. A black line on a white floor is attached to the movable part of the inject printer, and the optical sensor module was fixed. The height of the optical sensor module from the white floor can be adjusted to check whether or not the resistance values in Figure 2b are appropriate. The patterns of the 7 reflective optical sensor outputs, when the track on the linear platform is moved from 130mm to 220mm after calibration, is shown in the upper-left of Figure 6, which shows the patterns are quite similar after calibration. The other 3 plots in Figure 6 show the experimental verifications of the line detection algorithms via weighted average (lower-left), and quadratic interpolation (lower-right) respectively by using calibrated sensor outputs. The mean-square-errors (MSE) of these methods are also shown in the titles of these plots. It was seen that the line detection algorithm via weighted average has the least mean-square-error, although the mean-square-error for the method of linear interpolation is only a little bit bigger.

AUTOMATIC CONTROL ALGORITHMS FOR THE LINE-FOLLOWING ROBOT

The popular proportional-integral-derivative (PID) controller was introduced in this project to make the robot follow the racing track [16]. The error between the centre of the reflective optical sensors and the track to be followed was then processed by the PD controller in Figure 7 to generate velocity commands for the right and left wheels. The proportional term is only a gain amplifier, and the derivative term is applied in order to improve the response to disturbance, and also to compensate for phase lag at the controlled object. The D term will be required in most cases to stabilise the tracking motion. Although the integral control is not used, the steady state error is small enough and does not cause too much trouble.
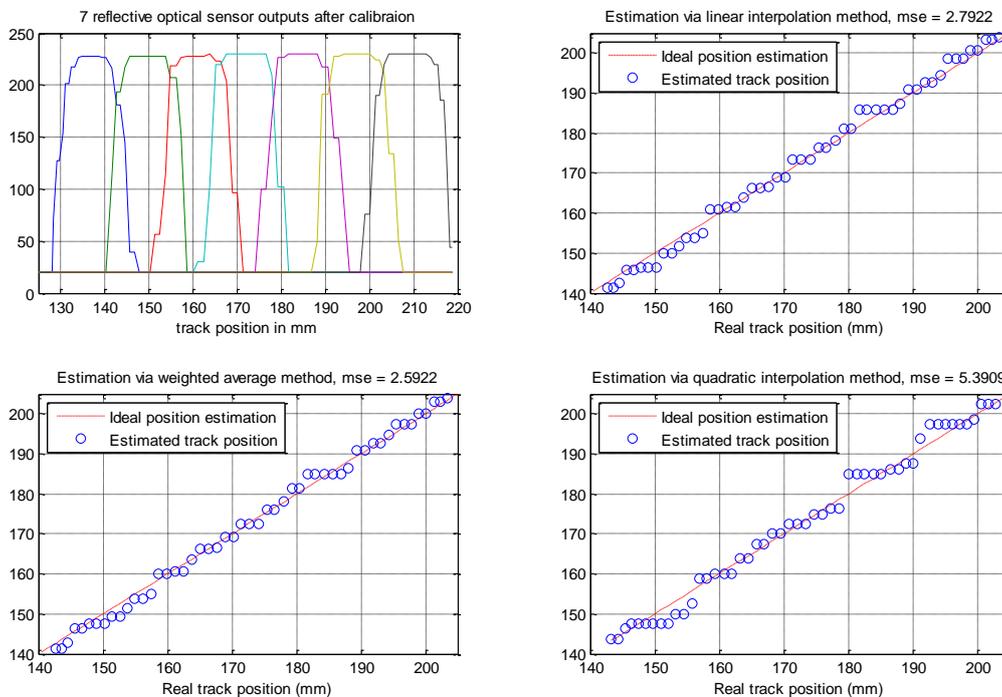
Figure 6: The experimental comparisons of various line detection algorithms by using calibrated sensor outputs.
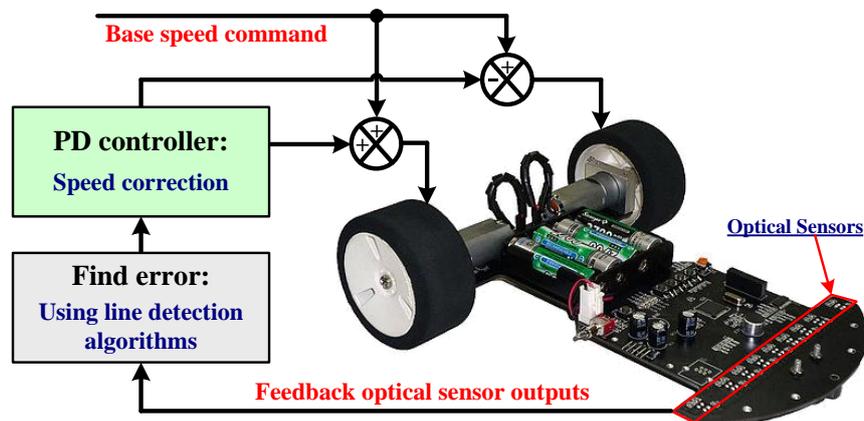
Figure 7: The automatic feedback control structure for the intelligent line-following robot.

WORKSHOPS AND CONTESTS

The idea described in this article has been used for two years in workshops for vocational high-school teachers and students in Taiwan. The workshops are supported by the Ministry of Education and, therefore, the workshops are free. All the vocational high schools are also given free line-following robot kits to help speed the learning process. To see how well the participants integrate all the skills learned in the workshops to implement line-following robots, a race was held after the hands-on laboratory was finished (Figure 8).

The results have shown that the line-following robot, when integrated with a conventional curriculum, was very helpful in motivating students and keeping their interest high. Winning one or two awards at a competition not only gives students a sense of accomplishment but also pride and visibility to their schools. This is an important factor for technology-oriented high school students in Taiwan, because of their low learning in traditional theory-oriented lecture courses. The student far left in Figure 8, who won second prize in the national contest (shown in Figure 8), is such an example [5].

Figure 8: The free workshop and contest for vocational high school teachers and students at Lunghwa University of Science and Technology.

CONCLUSIONS

A description of an intelligent line-following robot for introductory robot courses is presented in this article. The intelligent line-following robot was a revision of a previous design that won some national contests. An automatic calibration procedure for reflective optical sensors using pulse-width-modulation techniques was proposed and verified.

Three different kinds of line-detection algorithms are also described and experimentally compared by using a linear platform following the calibration procedure. It was found that the weighted average line-detection algorithm was the best in these line-detection methods using mean square errors. A homemade encoder was also devised to help the firmware remember all the information of the racing court. When all these functions were put together in the intelligent line-following robot, the average speed could be 1.3m/sec.

Although this outcome is still not good enough to compete in an international *Robotrace* contest, the ideas all proved to work well in a test racing court. The line-following robot also can be used in an introductory robot course since it requires knowledge of sensors, motor control, calibration and line-detection algorithms. Most of all, it is not expensive.

Several laboratory exercises have been designed and offered to vocational high-school teachers and students in Taiwan, and the feedback from workshop participants was quite good. One of the students even won second prize for line-following robots in a national contest.

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