Industry-Orientation Training Course by Line Following Maze Robot

Hsin-Hsiung Huang[1], Chyi-Shyong Lee[2], Juing-Huei Su[3], Chia-Lung Yang[4] and Tsai-Ming Hsieh[5]

***Abstract*—**This study provides a robot industry-orientation training course which integrates the hardware circuits, firmware programming and shortest path algorithms into the implementation the line following maze robot. The objective of this work is to attract students' interest in industry skills such as design of hardware circuits, firmware programming and path-finding algorithms. The robot training course has several key components, including 1) the five sensors to detect the routing path (line position), 2)UART transmission and the corresponding firmware codes between two micro-controllers, 3) the robot motions with the corresponding firmware programming and 4) a shortest path algorithm for the tree-based routing map and path-merging algorithm for the cyclic-based routing map. After finishing this course, students learn many practical skills, including designing the sensors to guide the robot, developing a UART-based protocol and its corresponding firmware code for two micro-controllers, and implementing a shortest path algorithm for a tree-based map. Moreover, we also provide the programming exercise for the cyclic-based routing map. We merge the same paths after we analyze two different routing paths which are obtained through separate algorithms. Hence, total routing path could be further reduced. The price of this line-following maze robot is cheap (~USD$150) and the course materials, including the necessary theories for embedded systems, firmware for motion control, and the shortest path algorithms, are interesting to draw students' attentions. Finally, we design some questionnaire to measure the performance of students and modify the materials according the feedback from students.

***Keywords*—**Industry-based, line-following maze robot, path-merging algorithm, shortest path algorithm.

I. Introduction

Mobile robots are becoming more and more important for certain some daily life applications. The necessary skills, such as electronic design, automatic control theory and algorithms, are usually too difficult for students. We observe that students are easily interested in an intelligent robot. Generally, they would like to study difficult theories, such as the electronic circuit design, the control theory and complex kit. How to arrange a mobile robot system training course that teaches students the theories is important.

Many research studies focus on hardware- aware training courses, learning tools and materials to improve the quality of engineering education for students. The authors provided a new approach to improve the teamwork for students and gave assessment methods to avoid some problems [1]. The work studied the industrial example and motivated the interests of engineering students to study mathematics [2]. This paper explored the application of electronic equipments for sixth-grade students and observed that the course designer should improve the materials [3]. This study investigated some approaches to overcome the disadvantages of traditional control materials. The block diagram and graphic user interference for control system are provided to improve the course quality [4]. Li *et al.* [5] provided the computer-aided design tools to speed-up the learning procedure and laboratory experiments were given to increase the understandings for the difficult theories. Moallem *et al.* [6] developed a temperature platform from which students can learn to implement the practical skills to control embedded systems. The authors [7] presented a line-following robot that integrated the electronic circuit design and programming skills. Dupuis *et al.* [8] developed a line-following robot to dynamically search line position, and they applied the genetic algorithm to simulate the behavior of a robot. Skaff *et al.* [9] designed a special hexapod robot to perform straight-movement and line-following by using the optical sensors and the six legs. Huang *et al.* [10] investigated the training course to simultaneously discuss the hardware design, firmware for motion control and the shortest path-finding algorithm. It is a novel training course to train students to learn the abilities of the hardware implementation for a platform system, the firmware for motion control and the searching algorithm. Some works only focused on the hardware circuits implementations. Some papers investigated the integrated training courses to simultaneously dress the hardware and software techniques, but most of them did not explore the industrial skills of the hand-on laboratory experiments. How to make students learn industrial skills to increase their ability is important.

The main contributions of this work are as follow. First, a mobile robot system, which contains two micro-controllers to control the system, five optical sensors to detect line positions, and several motion types for quick robot movement, is explored. By finishing the line-following maze robot, students can learn

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the practical industrial skills, including the hardware circuit design, firmware programming for motion controls and control the time interval for peripheral devices. Second, two interesting and important problems are proposed to train students in the ability to create shortest-path algorithms. For the tree-based map, students can modify the algorithm with the different searching priority of directions and study how to design the data structure to store the routing paths. For the cyclic-based routing map, we proposed a path merging algorithm to further reduce the shortest path from the dedicated source to the target. The programming exercise makes students solve the problem by analyzing the individual and same routing paths and providing algorithms to achieve this objective.

The rest of the paper is as follows. Section II describes the training course package, including the architecture of the course and the teaching design flow. Section III discusses the hardware circuit design and motion control. Section IV describes the software design and shortest path algorithms. Section V illustrates learned topics and feedback from the student after they implement the robot system. Conclusions are attached in Sections VI.

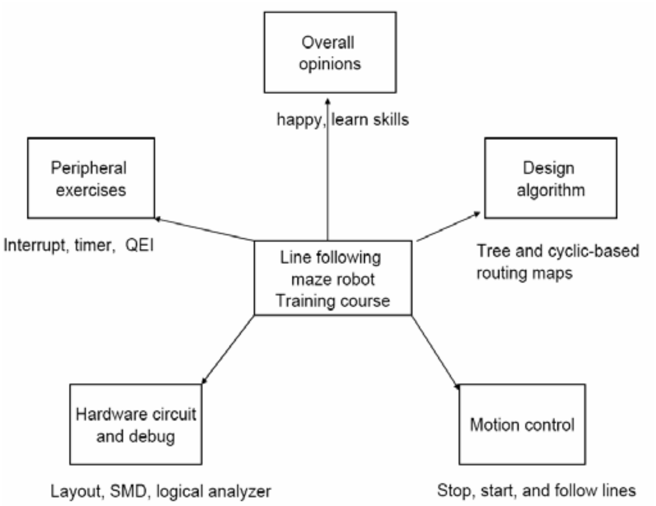


Figure 1: The architecture of training course.

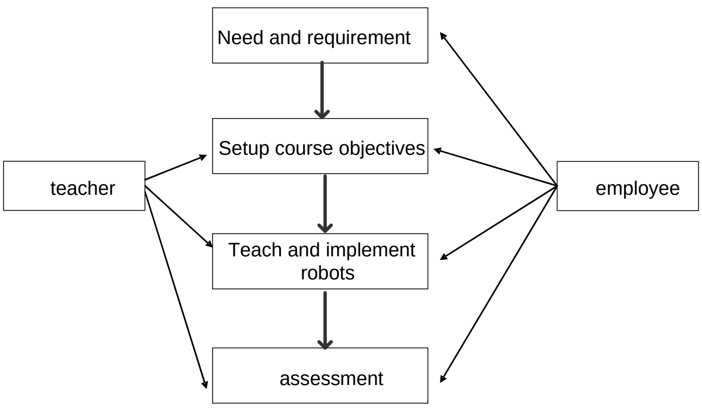


Figure 2: Design flow of training course.

II. Training Course Package

In this subsection, we will discuss the outline of the training courses. It contains the hardware circuits and debugging techniques, the peripheral exercises, motion control, design shortest path algorithm and the overall opinions. To implement the robot platform, we should prepare the set of sub-modules that correspond to the industrial skills. The objective of this training course focuses on the implementation of the sub-systems, which are discussed in the architecture of the training course. When students finish the topics step-by-step, they simultaneously develop the ability to design the hardware circuits, automatic control, firmware programming and the shortest-path finding algorithm. Figure 1 illustrates the order of the topics for students to achieve the objective of the training course.

The industry-based training course is integrated into the design flow. The industry employee first provides the need and requirement of the industry. Second, the objective of the course is setup after discussion between the employee and the teachers. According to the course objective, teachers design and arrange the course materials and the experiment platform. Finally, the proper assessment which generates according to the demand of the employee is applied to measure the performance of students. Figure 2 describes the teaching flow for students.

III. Hardware and Motion Control

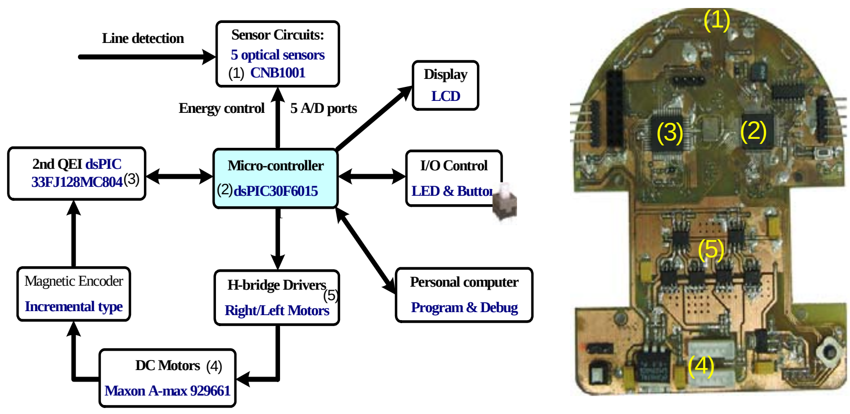
In this section, we discuss the topics, including a block diagram of the hardware circuit design, the optical sensors, UART-based transmission for micro-controllers and the predefined motion control.

A. Description of Hardware Block Diagram

A block diagram of the robot is shown in Figure 3(a). In the design, two micro-controllers (dsPIC30F6015 and dsPIC33-FJ128MC804)[11][12] are used to support enough encoders for two DC-motors, five optical sensors (CNB1001), and a LCD display. Figure 3(b) lists the corresponding real circuit of the robot. The important topics of the training course are the normalization of the optical sensors and application of UART-based communication and predefined motion controls. The firmware codes are downloaded to the memory in the robot. Meanwhile, students design the programming codes for the shortest path algorithm and update the firmware of the robot by using the ISP interference. Due to space limitations, only key topics such as the hardware block diagram, the optical sensors, the micro-controllers transmission and motion control are illustrated in detailed.

B. Optical Sensors

To improve the variation of the sensors, the normalized technology in [10] is applied. Hence, the maze robot can detect the line position accurately after normalizing all optical sensors. To avoid the interference and superposition among adjacent optical sensors, we take two important factors into account. One factor is the distance between two adjacent sensors and the other is the length from the ground to each sensor (Figure 4).



(a) (b)

Figure 3: Illustration the block diagram and hardware circuits.

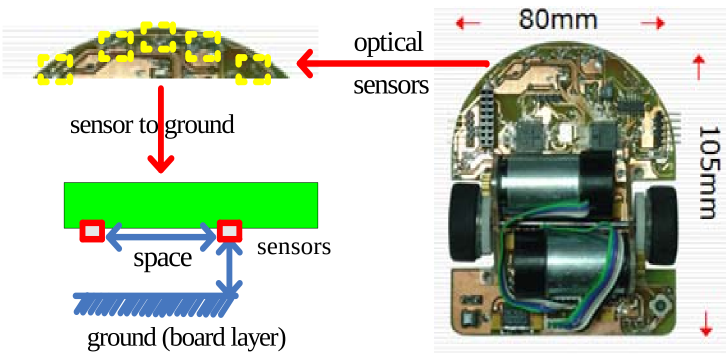


Figure 4: Illustration of optical sensors.

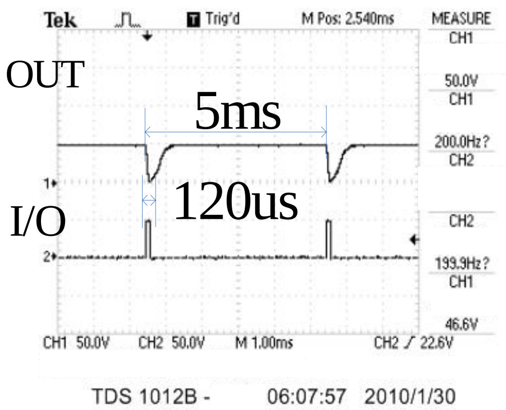


Figure 5: Waveform to illustrate power saving.

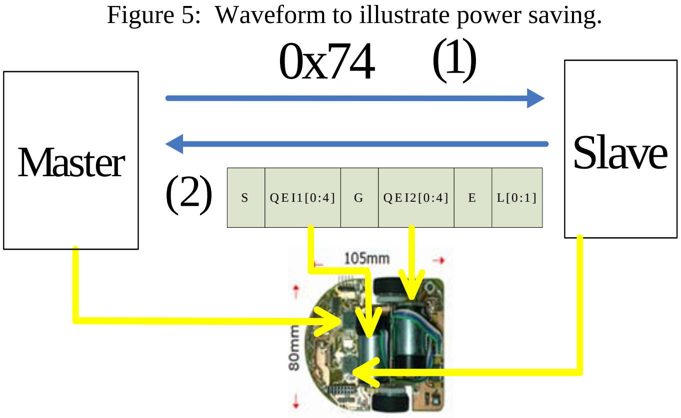


Figure 6: Data coherent for two micro-controllers.

In the robot, we save the power consumption of the optical sensors by integrating a sub-circuit. We observe that the optical sensors always turn on and total power consumption is excessive. Later, the power-gating technique, which turns off the sensors during idle status, is utilized to reduce the power of the robot. As shown in Figure 5, the improvement on total power is calculated by the formula $100\times(5-0.12)/5$ (=97%). It means that the micro-controller turns on the sensors for a period of 120us per 5ms.

According to the above descriptions, students can learn how to analyze the electronic circuit for the optical sensors and power-saving techniques.

C. UART Transmission Protocol

Due to the specification, one micro-controller does not have a high enough numbers of DC-motor encoders to achieve the demand of the line- following maze robots. Moreover, the "timer" of the micro-controllers estimates the distance. The timer-based method to estimate the distance is inaccurate to construct the real routing map. Due to these two reasons, the course, which applies the UART packet format of Figure 6 to receive and transmit the data between two micro-controllers, is used to teach the concept and implementation of protocol for two micro-controllers with encoders to students. In the course, two micro-controllers, including one slave dsPIC33FJ128MC804 and one master dsPIC30F6015, are applied to estimate the more accurate distance by the DC-motors. Summary, the master-slave protocol, which is based on the UART communication, is presented. The UART-based packet contains several components shown in Figure 6. When the master dsPIC30F6015 transmits the data "0x74", the slave dsPIC33FJ 128MC804 transmits the encoded values of two DC-motors, where S and E are the starting and ending of the packet. $QEI_1[0:4]$ and $QEI_2[0:4]$ denote the two different QEI-related data of the two DC-motors. G and $L[0:1]$ are the gap between two QEI-related data and the ending line symbol ("\r\n"), respectively.

To determine if the data of the packet transmitted and received successfully, students can learn the UART-based protocol shown in Figure 6.

D. Motion control

It is a challenging problem to make the robot move smoothly along the black line position. To achieve this objective, students should learn to program the firmware codes to control the primary motion, such as go-straight, turn-right, turn-left and turn around at the end of line. By combining several primary motions into the complex motions, the operation of robot will move smoothly and efficiently. For example, if the robot operates the go-straight or turn-back at the corner, we create several pre-defined motions, including line-following, L-turn, R-turn and U-turn. For the T-shaped or crossroad, the straight-right-turn (SR-turn for short) and left-right-turn (LR-turn for short) are implemented. In Figure 7, the robot moves from source to target by a combination of line-following (motion 1), R-turn (motion 3) and SL-turn (motion 6), respectively.

When the robot operates a motion, the firmware programming will run the dedicated sub-routine. Actually, each motion corresponds to a sub-routine. Primary and complex motions denote the simple motion and the combination of simple motions. A primary motion performs the simple motions that denote the following line, turn-right direction and turn-left direction. A complex motion type contains the combination of primary motions. For example, when the robot performs LS-turn (motion 6) at the T-shaped crossroad, micro-controllers runs the corresponding sub-routine.

At each crossroad, we should update the information, such as the straight-, right-, and left-directions, to record the routing map. It means that when we go to each node, we should define three variables (denoted by S, R, and L) to record the status of the routing paths. In Table 1, the first, second and third columns denote the straight-, right-, and left-directions status of each crossroad, respectively. For the status at each node, the corresponding motion types are shown in the fourth column of Table 1. For example, the R-turn type means that the robot turns right and only the right side at the crossroad has the routing path (we have R=1, S=0 and L=0). According to the above discussion, we know that when a robot performs a motion type, the sub-routine motion is called. Therefore, the firmware will select R-turn among the all motion types because the crossroad only has the right-direction routing path. Similarly, this information is stored by three variables (R, L and S) and the corresponding motion type is generated. By the motion type, the firmware will select the corresponding sub-routine to perform. By learning to design sub-routines, students make the firmware codes perform efficiently.

From the above discussion, students can learn firmware programming skills, the register configuration and the concept of sub-routine.

Table 1. Mode for motion control

S	R	L	Mode of node
0	0	1	L-turn
0	1	0	R-turn
0	1	1	T-shaped
1	0	0	S-turn Follow line
1	0	1	T-shaped
1	1	0	T-shaped
1	1	1	+-shaped

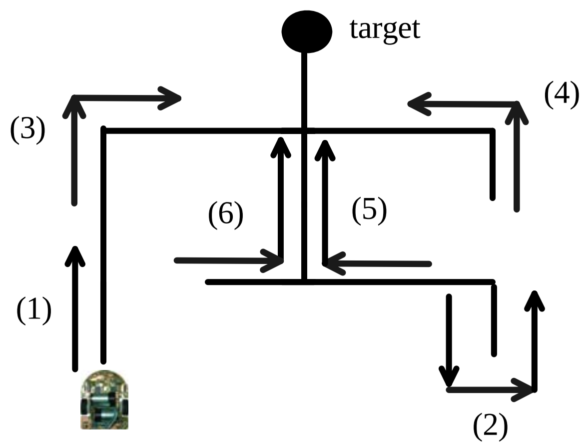


Figure 7: Motion types.

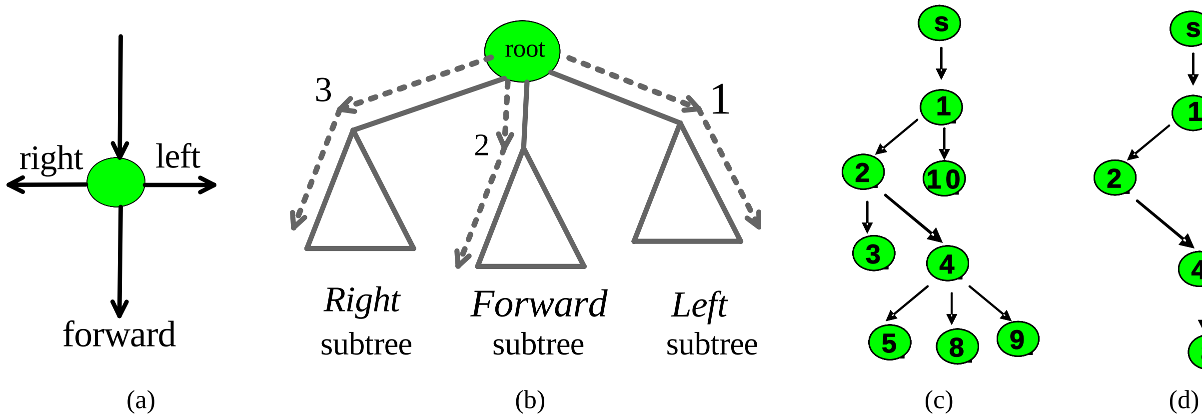


Figure 8: Illustration of shortest path algorithm.

IV. Software Design and Shortest Path-Finding Algorithm

In this section, we formulated two problems and used them to train students for industrial skills, including data structure, programming, and algorithm. We discuss the topics as follows.

A. Problem 1: Tree-based routing map

[10] defined the tree-based routing map and developed the shortest path-finding algorithm. For a tree-based map, a robot at the source will search the dedicated target. The concepts in [13][14] are applied to formulate the problem. The corner points, crossroad and T-shaped roads are regarded as the set of nodes, and the routing paths are considered as the set of edges. The objective of this work is to obtain the shortest path from source to target. Figure 8(a) is the routing map and Figure 8(b) is the corresponding tree-based structure.

[10] also provided RFL algorithm which searches each node by the concept of priority of right, forward and left-directions. Similarly, FRL method is implemented by adjusting the visiting priority. In other words, FRL searches the crossroad with the order of left-, forward- and right-direction. A shortest path will be produced after we search the tree-based map. Figure 8(c) is the searching results by applying RFL algorithm and the small memory usage in Figure 8(d) is used to store a shortest path.

From above discussion, students can develop the ability to define the problem and store the routing path with less memory.

B. Problem 2: Cyclic-based routing map

For a cyclic-based routing map, we observe that the merge-path technique can be used to further reduce the shortest path from source to target. When we obtain two different sets of information about routing paths from two searching algorithms (RFL and LFR), a path-merging algorithm is investigated to merge same routing paths.

The path-merging algorithm containing several steps is used to reduce the routing path. First, RFL algorithm, which visits each node with the predefined priority of right-, forward- and left- directions, is applied. A shortest path is produced after applying the RFL to visit the cyclic-based map. Second, LFR algorithm which visits the crossroads with the priority of left-, forward- and right-direction is applied to get the shortest path, too. Third, we analyze the information of two routing paths by RFL and LFR algorithms. We keep the same routing path among the information of routing paths. We select the shorter path for the individual paths by RFL and LFR. Summary, we apply the C++ language to implement a path-merging algorithm, and obtain the shortest path. The outline of the proposed algorithm is shown in Figure 9.

It is very important to analyze and merge the information of routing paths. Some data structures consume large amounts of memory and lead to long searching time for segments. In this paper, each routing paths is divided into a set of vertical or horizontal segments. For each segment, the coordinates store the starting and ending nodes. The data structure stored the coordinates of the starting and ending nodes and efficiently extracted to compute the length of routing path.

Algorithm: A Path-Merging Algorithm
Input: A robot and the cyclic-based routing map
Output: A shortest path from source to target.
Begin
1. Apply RFL algorithm to get the routing paths;
2. Apply LFR algorithm to get the routing paths;
3. Analyze the routing paths to keep the same path and merge some paths;

end.

Figure 9: Outline of path-merging algorithm.

We illustrate the concept to analyze the same and individual routing paths. The flag is used to denote the segment status (same or individual) of two different routing paths. The individual paths are set to be “1” and the same paths are set to be “0”. According to the status, in the programming exercise, we keep the segments (=1) and select the short segments (=0).

An example is used to illustrate the path-merging algorithm. Figure 10(a) denotes the original routing path. First, RFL algorithm is used to obtain the source-to-target shortest path in Figure 10(b). Second, LFR algorithm is again applied to visit the cyclic-based map in Figure 10(c). Third, we analyze the global routing paths shown in Figures 10(b) and (c). The dotted-lines and solid-lines denote the shortest paths by applying RFL and LFR algorithms. Furthermore, the routing path is reduced after we select the shorter individual routing paths. In other words, students can learn the proposed path-merging algorithm to automatically search the shortest path. Figure 10(d) is the final routing path after we analyze the same and individual routing paths from the different searching procedures.

From the programming exercise, students can learn algorithms and merge same paths to reduce routing path.

V. Learned Topics and Feedback

In this section, we discuss the feedback from students after they finish the learned topics of the training courses by implementing the line-following maze robot. This training course contains 18 classes which are shown in Figure 11, and each topic is assigned 3 hours. After 18 weeks for the training course, a robot contest is held to show the results of line maze robot implementation and students give their opinion by answering the questionnaire shown in Tables 2 to 7.

A. Learned Topics

The necessary knowledge of the following topics used to implement and design the intelligent robot are described and shown in Figure 11. The knowledge of topics 2, 4, 5 is used to enhance the ability of hardware design. Learning topics 3, 8 and 10 are used to make students control the robot movement. Furthermore, the learning topics 1, 6, 7 make students design and analyze the searching algorithm. Finally, the training course provides students with the necessary knowledge and skill about robot-related works. Figure 12 shows the related topics about the robot course.

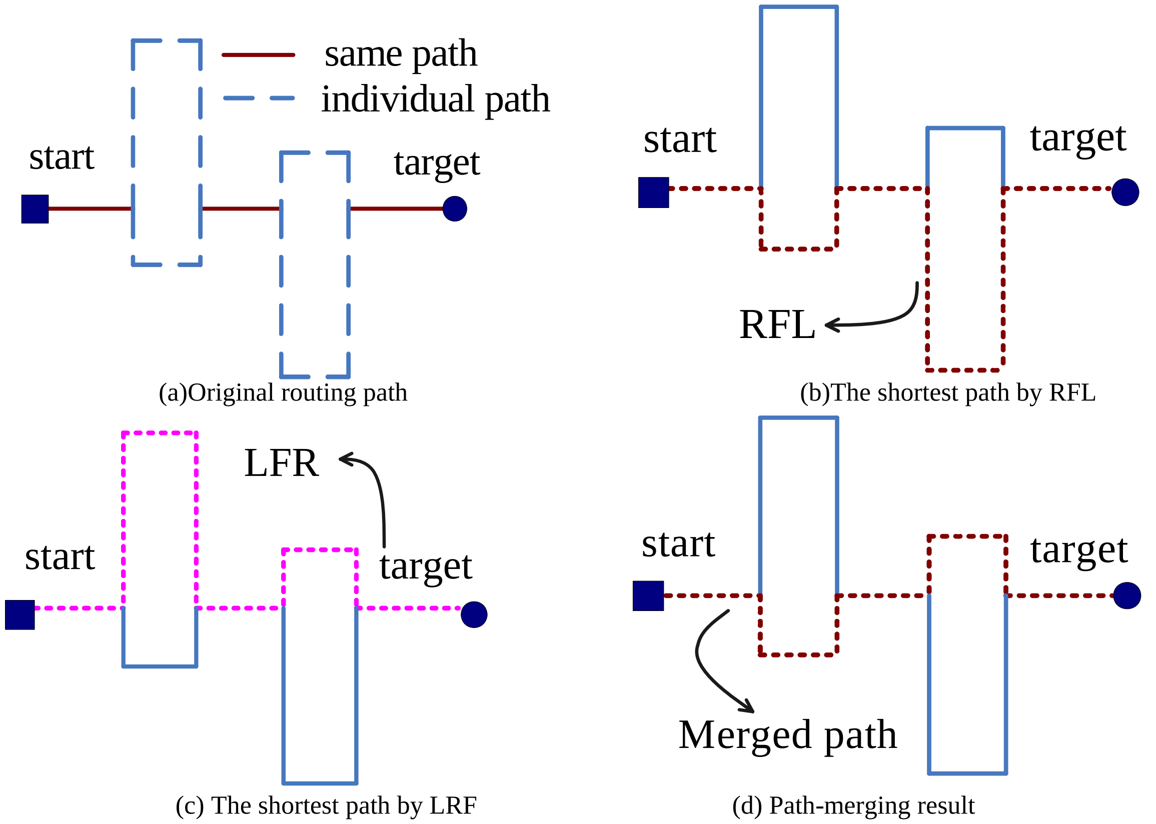


Figure 10: Path-merging algorithm.

B. Questionnaire

According to the training course topics shown in Figure 11, Tables 2 to 7 show the questionnaires to measure the learning situation from students. We properly adjust the training course topics and course objective in Figure 2 from students' feedback.

Table 2 summarizes relationship between five topics in questionnaire and course topics. Table 3 lists the questionnaires of overall viewpoints about this course. Students assign the proper score from one to five for each question. Table 4 illustrates the measurements of hardware circuits design and debug. Each question is used to measure if students learn the industry skills to draw circuit layout, mount the SMD components.

After finishing the circuits, students also learn the debugging concepts and apply the scopes and logic analyzer tools to capture and get the timing waveform. Moreover, students must know and describe the operation of two micro-controllers.

Table 2: Questionnaire topics

Course topics	Questionnaire topic
Topics 1 ~ 10	Overall viewpoints
Topic 2	Hardware circuits and debug
Topics 1 ~ 5	Puerperal exercises
Topics 1 and 6	Motion control
Topics 6 ~ 10	Design algorithms

Table 3: Overall viewpoints (points: 1-5)

The implementation and design of hand-on laboratory is well-arranged.
I am glad to study this class
I will encourage my classmate to learn this class
This class teaches us implement the robot by myself
I learn the skill to control the motors, optical sensors and micro-controller

Table 4: Hardware circuits and debug (points: 1-5)

I can mount the SMD components
I can design layout by Protel 99SE
I can capture the waveform by waveform generator
I can analyze the timing by logical analyzer
I can describe the function of micro-controllers

Table 5 shows the exercises for peripheral components. Figure 11 discussed the course topics in peripheral. Therefore, the questions are used to check if students learn the basic concept of C language. Moreover, students apply the C language to interrupt and calculate position of two DC motors. The communication between two micro-controllers is also implemented by UART-based protocol.

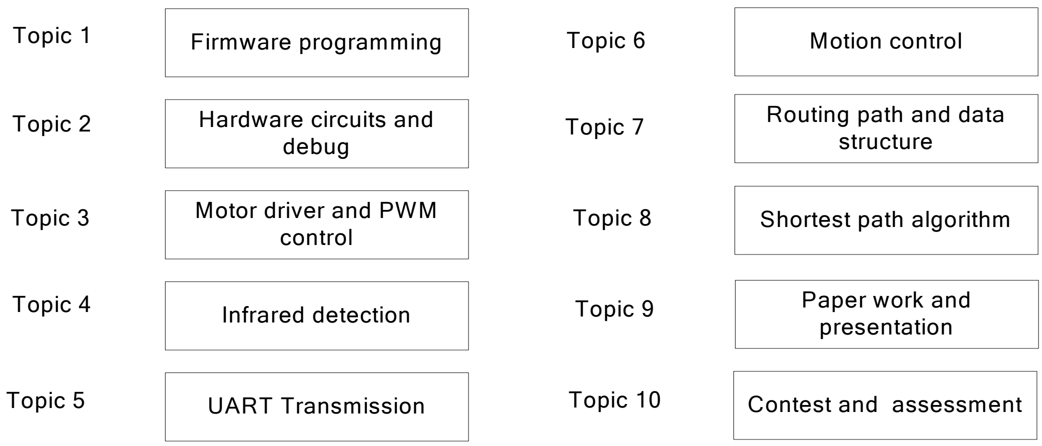


Figure 11: Design framework and the course topics.

Table 5: Peripheral exercises (points: 1-5)

I can distinguish the different types of C language
I can perform the interrupt by setting registers
I can read the QEI values from two DC motors
I can read the gray value of optical sensors
I can transmit the data by URAT protocol

Table 6: Motion control (points: 1-5)

The robot can perform start and follow line
The robot can performs R-turn and L-turn
The robot can performs SR-turn and LR-turn
The robot can performs U-turn
The robot can performs stop

Table 7: Design algorithms (points: 1-5)

Transfer the routing map into the graph model
Use the data structure to store all routing paths
Distinguish the difference between the tree-based and cyclic-based routing map
Search the shortest path by given the priority for a tree-based routing map
Finish the programming exercise of merging path for the cyclic-based map

Table 6 lists the motion control that the robot should perform. Figure 5 demonstrates the primary motion and the questions in Table 6 are used to check if students learn the necessary skills. Additionally, Table 7 shows questions about algorithms. We want students to learn the ability to store routing paths information with a proper data structure. Therefore, the algorithms can speed-up the searching time to obtain the shortest path. Moreover, a cyclic-based problem is used to train students to analyze the routing paths and reduce the redundant path to minimize the routing path.

Actually, the line-following maze robot moves efficient and effectively finds the shortest path. The robot won the first prize in "Domestic University Group Micromouse and Robot Design Contest" [15]. The award motivates students who joined the contest to actively study the related topics and further improve the robot. Figure 11 lists the topics in the industrial-based training course. These topics are divided into three types, such hardware circuits, firmware programming and the path-finding algorithms. Figure 11 is the overall framework to this robot course. The framework contains the hardware circuits, firmware codes and algorithms. Summary, we integrate related topics in Figure 11 into the framework in Figure 12.

Summary, the course materials, such as the experiments and documents, makes students learn the industry-based skills. The material which contains hardware design, the electronic circuit, control theory and shortest path algorithms is difficult enough for students. They feel satisfied and become more interested in the robot source when the self-designed robot works normally by integrating the hardware, firmware codes and the searching algorithms [10]. The feedback from students can further improve the objective and course content.

VI. CONCLUSIONS

In the work, a robot system course is provided students with industry skills, especially for the firmware programming. We observe that the award of the contest motivates student to actively learn the difficult topics and improve the performance of their line-following maze robot. From the framework of the training course, students learn industrial skills, control theory, circuit layout and algorithms for tree-based map.

In the future, we will integrate the complex routing map such as the cyclic path in a graph into the robot system instead of the programming exercise. We want to modify some graph-based algorithms, such as Dijkstra, depth-first search [13][14].

VII. ACKNOWLEDGEMENTS

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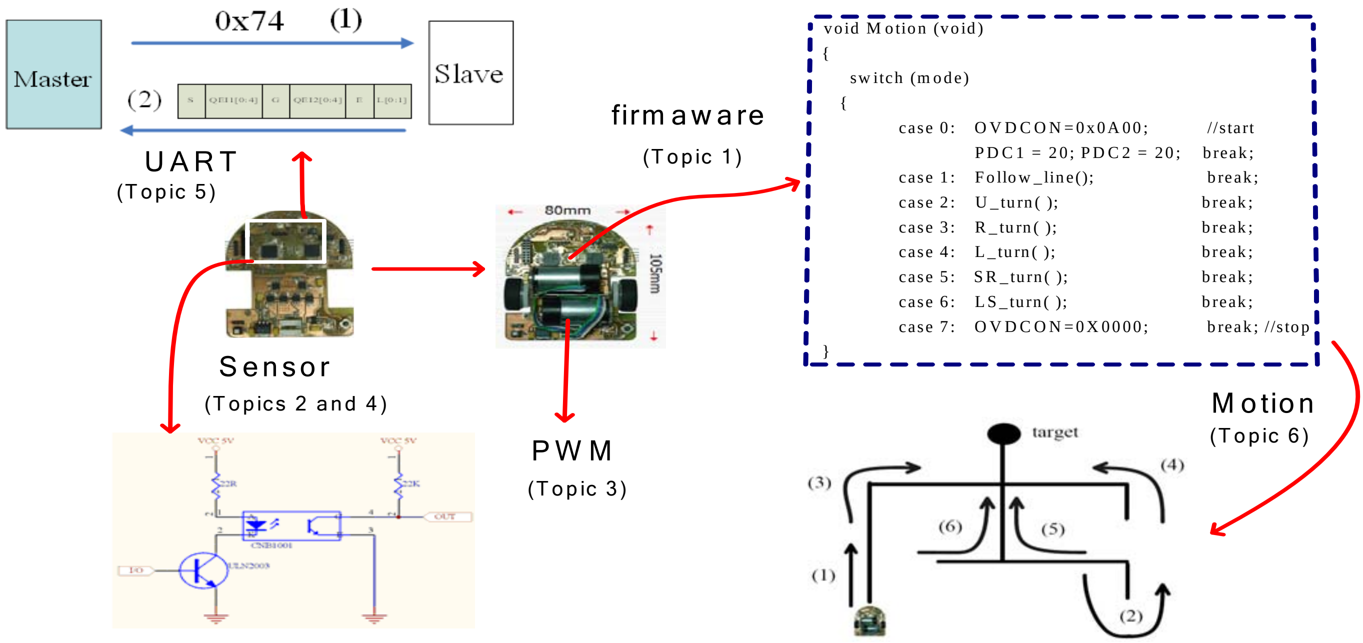

Figure 12: Design framework and the course topics.

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