Multi-Sensors for Robot Teaming Using Raspberry Pi and VEX Robotics Construction Kit

Dr. Shouling He, Vaughn College of Aeronautics & Technology

Dr. Shouling He is an associate professor of Engineering and Technology at Vaughn College of Aeronautics and Technology, where she is teaching the courses in Mechatronics Engineering and Electrical Engineering Technology. Her research interests include modeling and simulation, microprocessors and PLCs, control system designs and Robotics. She has published more than 45 journal and conference papers in these research areas.

Dr. Sheng-Jen "Tony" Hsieh, Texas A&M University

Dr. Sheng-Jen ("Tony") Hsieh is a Professor in the Dwight Look College of Engineering at Texas A&M University. He holds a joint appointment with the Department of Engineering Technology and the Department of Mechanical Engineering. His research interests include engineering education, cognitive task analysis, automation, robotics and control, intelligent manufacturing system design, and micro/nano manufacturing. He is also the Director of the Rockwell Automation laboratory at Texas A&M University, a state-of-the-art facility for education and research in the areas of automation, control, and automated system integration.

Developing Teaming Robots for Engineering Design Education Using Cross Platforms

Abstract

The paper presents an engineering design approach to develop an instructional module for college students to learn Microprocessors and Robotics using multiple sensors, microprocessors and software design tools. The module consists of research analysis, lesson content development and laboratory practice selection, which satisfies the ABET (Accreditation Board for Engineering & Technology) requirement for engineering education. The research analysis covers the work reported by the scholars from MIT and other universities [1] [2], where the main concern is how to enhance students' capability in developing engineering products using new technologies in the industry, such as multiple sensor fusion methodology as well as working skills on cross-platform hardware (Intel, ARM, AMD and PIC, etc.) and software (Linux, Windows and Androids, etc.). After the research paper analysis, a class activity has been developed. The activity includes teaching students to build teaming robots by combining the Cortex controllers with ROBOTC programming environment under Windows and the Raspberry Pi (in ARM cores) using Python under Linux and guiding students to develop a cross-platform software and hardware design using PIC Microcontrollers with embedded C under Windows and the Raspberry Pi with Python under Linux.

The teaming robots under development contains a leading robot and a tracking robot. The leading robot in the front can turn in any direction. When it "sees" an obstacle ahead using an ultrasonic sensor, it will turn left or right to avoid the obstacle. The tracking robot has a Cortex controller to drive the motors and an ultrasonic range finder to detect the distance between it and the leading robot. At the same time, the tracking robot also holds a Raspberry Pi board with a Pi Camera on it. The image signal obtained from the Pi Camera is processed by the Raspberry Pi and sent to the Cortex controller. Based on the processed image signal, the second robot can follow the first robot to turn accordingly, thus, they make a robot team. The exercise package contains a PIC microcontroller with a speaker and the Raspberry Pi with Pi Camera. If the Pi Camera finds some motion around, a signal will be sent to the PIC microcontroller and the siren sound will be emitted. The activities largely aroused students' curiosity and attention. The survey result is very encouraging. After the class, students' enthusiasm in learning Python, image processing and engineering design using multiple boards and programming languages as well as the applications has been noticeably enhanced.

Key words: Teaming Robots, Camera, Cross-platform Hardware and Software Design

1. Introduction

As it has been predicted, in the mid-21st century, Artificial Intelligence (AI) will become more pervasive, potentially making every company and every employee smarter, faster, and more productive. In addition, autonomous vehicles will replace most cars and other transportation tools used today. Under the circumstance, as an educator, it is an urgent task for us to teach students to effectively adopt new technologies in the automation industry, for example, being quickly familiar with various types of cross-platform hardware and software design tools, as well as being capable to design a robot that can make intelligent decision based on multiple sensor inputs, particularly the inputs from computer vision devices.

However, to our observation, currently, in engineering education area, we still couldn’t find economical and robust robot systems for us to efficiently teach students multiple sensor fusion technology as well as control of a robot using a computer vision system. The report [3] introduced their experience to build a robot controlled by a handy board with the inputs of a camera and a sonar sensor. The Lego materials were used to build the robot body. Furthermore, some research work has been done to develop ball tracking robots using a camera [4]. However, due to the relatively complex image processing algorithm and camera requirements, most of the robots were built in a small size and fragile with less power and, therefore, may be not proper in robotics education. Considering that VEX robots have been popularly used in many universities and colleges for robotics education. On the other hand, some affordable microcontroller boards, such as Raspberry Pi and PIC Microcontrollers, are becoming more widespread in education, in this paper, we demonstrate an approach to design autonomous teaming robots by combining the Vex Cortex board and Raspberry Pi 3 board to teach cross-platform hardware and software design, and then provide students an opportunity to practice cross-platform design using a PIC Microcontroller board and a Raspberry Pi 3 board. For the teaming robots, the VEX Cortex controllers will be mainly used to drive various motors and process the data sent from small and less complicated sensors and the Raspberry Pi 3 board is primarily used to handle the image data using computer vision algorithms. Since the VEX Robotics construction kit save educators’ efforts to find motor drivers and other mechanical parts, the design can focus on more programming on the Cortex Controllers and Raspberry Pi using different programming languages and operating systems.

Notice that the proposed courseware is designed for the students who have had some experience in building VEX robots (with the completion of one credit course of Introduction to Robotics) as well as high-level language programming, such as C/C++, and some course practices in Microcontroller course using the PIC microcontroller board. Therefore, the paper will briefly introduce the VEX robotic body design and discuss more in detail about the introduction to the Raspberry Pi 3 processor, and the programming of Pi Camera in Python language, and finally develop the cross platform using PIC Microcontrollers with Raspberry Pi 3 and Pi Camera.

The paper will discuss the development of cross-platform designs in the following steps. In Section 2, the hardware and software used in the courseware are introduced. It includes a set of VEX Robotics Construction kit with a Cortex controller and the programming environment ROBOTC, a Raspberry Pi board, a Pi Camera and the programming environment, a PIC Microcontroller and its programming environment MPLAB X IDE. Section 3 contributes to teaching Python language and computer vision. The details of system implementation, i.e. color filtering to detect the movement of the first robot by the second robot, the control algorithm for the tracking robot and the flowchart of programs in ROBOTC and Python for the VEX Cortex controller and Raspberry Pi are discussed in Section 4. Student learning results and comments as well as some discussions are provided in Section 5. Conclusion is given in Section 6.

2. Hardware and Software Used

(1) VEX Robotics Construction Kit and Cortex Controller

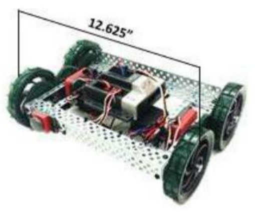


Figure 1: Chassis of the VEX Robot

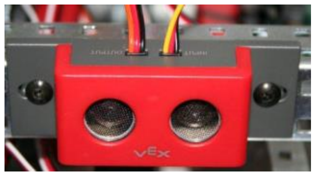


Figure 2: Ultrasonic Sensor

The VEX Robotics Construction kit [5] comes with a Clawbot Robot Kit, a Cortex®-based Microcontroller, a VEXnet Joystick and VEXnet Key 2.0, an assembly manual, and a robot battery and charger. Since the purpose of the educational device under development focuses on autonomous model of the robotic vehicles, the VEXnet Joystick and VEXnet Key 2.0 is not used here. However, another Cortex controller, which costs similar to the VEXnet Joystick, is used to control the second robot.

In addition to this kit, several ultrasonic range finders [6] were purchased and a programming hardware kit was also made available to the students to allow communication between a PC and the VEX Microcontroller. Since the robot chassis was built by the students in the course, Introduction to Robotics, the students are familiar with the hardware materials.

To program the VEX Robots, the ROBOTC Integrated Development Environment (IDE) [7], which is designed for VEX hardware, was utilized. The programming language is a simplified version of C language. Since the interface and standard programming language of ROBOTC is compatible to the environment and standards of those used in the industry, the IDE environment was chosen to write programs for the two VEX robots. Again, once the flowchart to program the VEX robots are clearly discussed, students can easily understand the programs.

(2) Raspberry Pi 3 Board and Pi Camera

Figure 3 shows the Raspberry Pi 3 Board [8], which is used for image processing. Table 1 shows the specification of the board. It uses the Broadcom BCM2837 chip with Quad ARM CPU- Core CPU and Dual-Core GPU in it with the CPU frequency of 1.2GHz. It has the RAM of 1 GB, micro SD card storage as well as the network function with Ethernet, Bluetooth and WIFI 802.11 protocols. Finally, it has one HDMI port, four USB ports, one camera serial interface, one LCD display serial interface and 40 GPIO (General Purpose Input and Output) ports. It runs with Raspbian operation system (OS) which is a Linux-like OS and makes it more attractive.

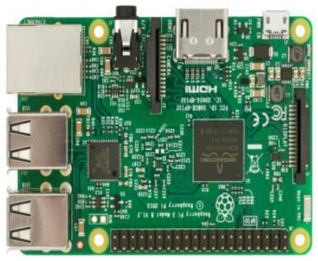


Figure 3: Raspberry Pi 3 Board

Figure 4: Raspberry Pi Camera Module V2-8

Table 1: Specification of Raspberry Pi

SoC	Broadcom BCM2837
CPU	4×ARM Cortex-A53, 1.2GHz
GPU	Broadcom VideoCore IV
RAM	1GB LPDDR2 (900 MHz)
Networking	Ethernet, 2.4GHz, 802.11n wireless
Bluetooth	Bluetooth 4.1 Classic, Low Energy
Storage	microSD
GPIO	40-pin header, populated
Ports	HDMI, 3.5mm analogue audio-video jack
	4× USB 2.0, Ethernet
	Camera Serial Interface (CSI)
	Display Serial Interface (DSI)

The Raspberry Pi Camera Module V2-8 is displayed in Figure 4. It's the second generation of Raspberry Pi Camera Module with fixed focus lens. It has 3280 (H) x 2464 (V) active pixel counts and maximum of 1080P30 and 8MP stills in Raspberry Pi board.

Raspberry Pi 3 with Pi Camera was programmed under Debian, a distribution of Linux Operating System, which is composed entirely of free software and packaged by a group of participating in the Debian Project. The detailed information for Debian can be referred to [9].

(3) E-blocks and PIC18F4580 Microcontrollers

PICmicro Multiprogrammer board, developed by Matrix Technology Solutions Ltd [10] has been used for students to do cross-platform exercises, as shown in Figure 5.

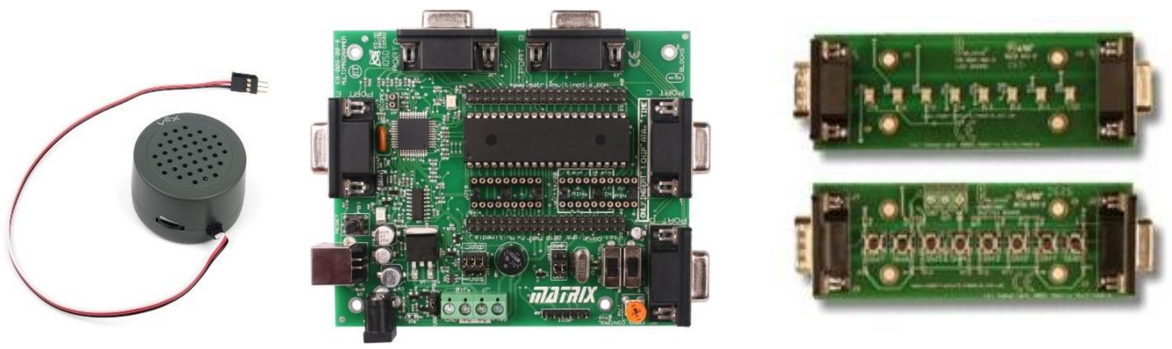


Figure 5: E-block Multi-Programmer Board with LED/Switch Modules and Speaker

The PICmicro board is a low cost and flexible microcontroller programmer. This board can be used with conventional microcontroller programs that generate hex code for the PIC family using MPLAB X IDE and a C compiler (C18 is used for the project). The board provides 'clean' access to all input/output lines on the relevant PICmicro microcontroller device. These are presented on 9-pin D-type connectors: 8 bits and earth. A range of additional E-blocks boards can be plugged into these D-type connectors to provide a rapid prototyping system for learning and development.

The total cost for all hardware is around $758.39. The price distribution is listed in Table 2.

Table 2: Cost for All Hardware Used in Project

No.	Name	Price ($)
1	Clawbot Robot Dual Control Kit	$439.99
2	Ultrasonic Range Finder x 2	$29.99
3	Raspberry Pi 3 Board	$64.99
4	Raspberry Pi Camera Module V2-8 Megapixel, 1080p	$29.49
5	Battery Pack for Raspberry Pi	$24.94
6	E-block Multiprogrammer	$115.00
7	LED Board in E-Block	$22.00
8	Switch Board in E-Block	$22.00
9	Speaker Module	$9.99
	Total	$758.39

3. Python Programming Language and Computer Vision

In order to develop the program for image processing using the Raspberry Pi board, Python language has been chosen. The reason for us to choose it is the language is easy to learn and portable for different computers. Particularly, it's suitable for processing a large amount of data, such as image processing.

Since students who attended the class had learned C/C++ programming language as well as programming a PIC Microcontroller using embedded C for 12 weeks (with the course Microprocessors), the lecture focused on the comparison between the two languages, embedded C and Python, in terms of (1) data types; (2) input/output statements; (3) control flow: if-statements and while/for – loops; function calls and include/import library and modules and classes.

After students were familiar with the syntax of Python program language, the fundamental knowledge about computer vision and digital image processing were discussed. The introduction started with the difficulty of digital image processing due to the transformation from 3D view into 2D image. Furthermore, the quantization of analog signal introduces the concept of pixels. For each pixel, the number of bright level can decide the clearness of an image as shown in Figure 6 (See [12] for detailed information). In digital image processing, whether the number of pixels and the level of brightness of each pixel change are important parameters for a processor to decide if the motion happens after it compares a sequence of image frames.

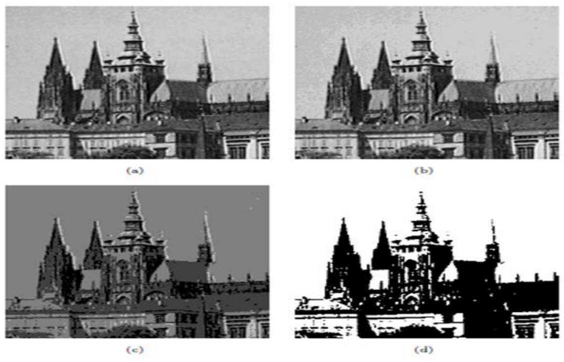


Figure 6: Bright Level (a) 64; (b) 16; (c) 4; (d) 2

4. Design and implementation of teaming robots

Using the VEX robotics construction kit with two Cortex controllers, two Vex robots have been built, as shown in Figure 7 and Figure 8, respectively. Raspberry Pi 3 and Pi Camera are installed in the second robot as shown in Figure 8.

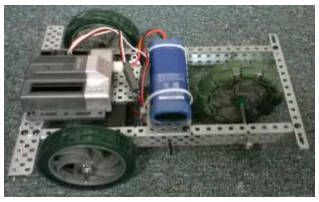


Figure 7: Leading Robot

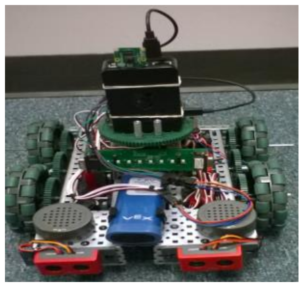


Figure 8: Tracking Robot

After the completion of robot building, next step is to decide the algorithm so that the second robot can follow the first robot autonomously. We completed the design in following steps:

(1) Determination of the color for the second robot to detect and color filtering

To identify the first robot's position, a red color board is mounted to the back of the first robot, as shown in Figure 9.

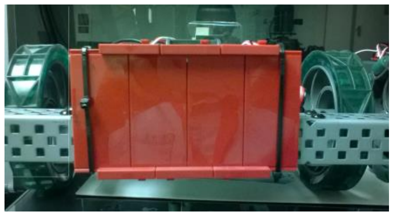


Figure 9: Red Symbol Board on the Back of the First Robot

After the color is decided, the program to select the threshold for the color parameters H (hue), S (Saturation) and V (Value) is run. After the adjustment of HSV values, the upper boundary of the red color is selected as [190, 255, 255] and the lower boundary of the red color is [160, 160, 10]. Using the two sides of threshold, the mask area of the red symbol board is identified as shown in Figure 12 when the second robot is in the back of the first robot as seen in Figure 11.

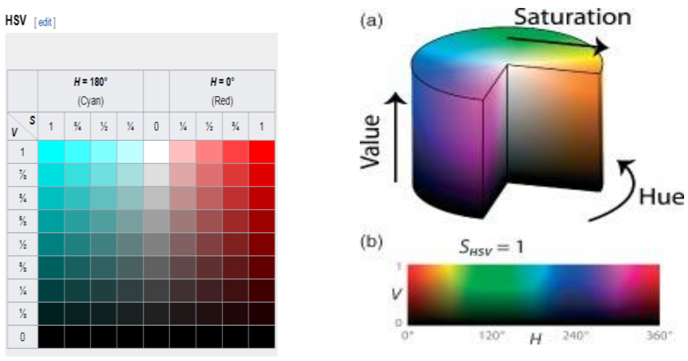


Figure 10: HSV Definition for Image Processing

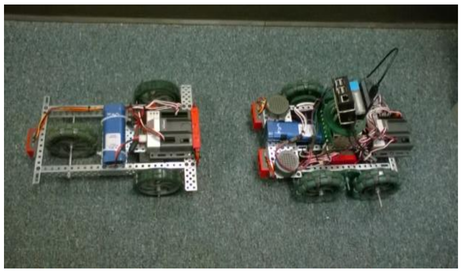


Figure 11: Positions of Two Robots

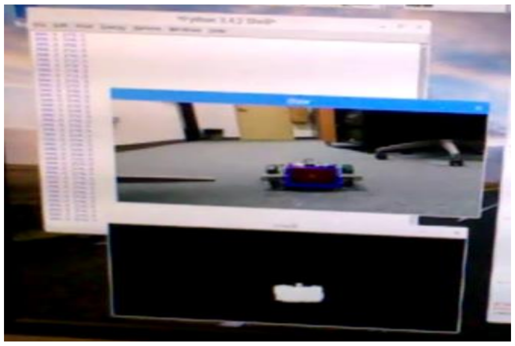


Figure 12: Image from Pi Camera and Mark Image

(2) Development of control algorithm

After the target symbol board is identified, the following step is to control the behavior of the tracking robot according to the movement of the leading robot, which means if the white mask shown in Figure 12 moves to one side (the leading robot turns to the side), the tracking robot should turn to the side accordingly so that the mask is kept in the middle position of the image frame.

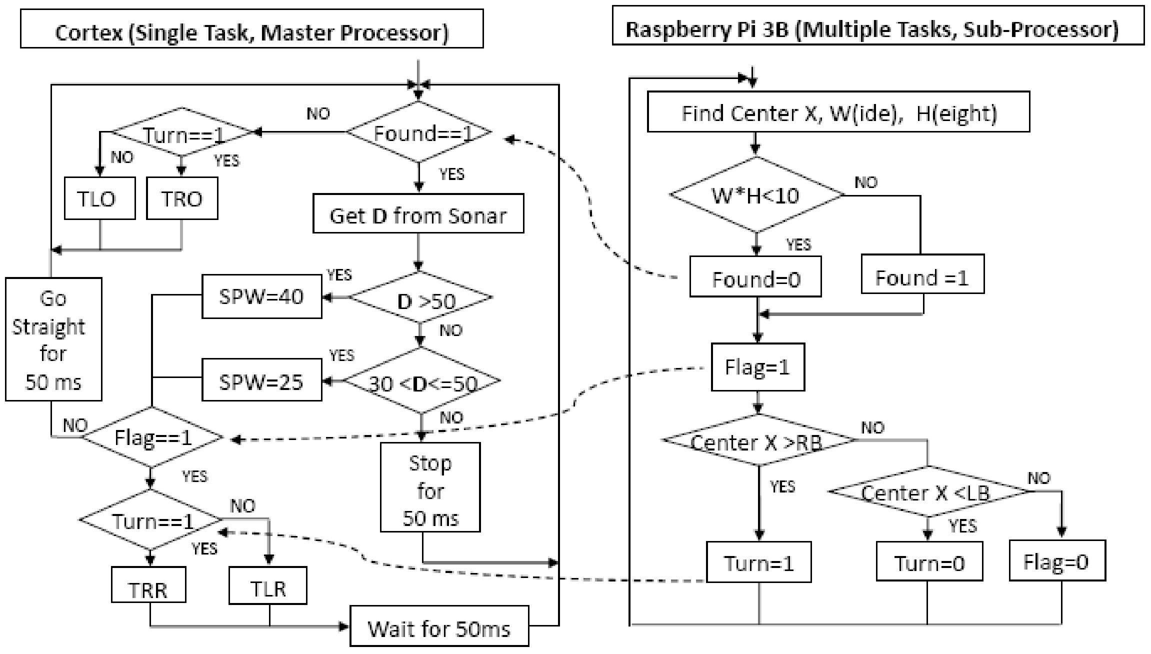
In order to find parameters of the control algorithm, an experiment shown in Table 3 was conducted. As Row# 2 and Row #3 show the first robot in the left side of the second robot with the angle of 22˚ and the distance of 51 cm, the center x value is between 188.5 and 200.5. When the first robot is in the right side with the angle of 22˚and the distance of 51cm, the center x value is between -19.5 and -15.5. Row#1 shows that if the turning angle is zero, the center x is between 90 and 95. Based on the measured result, we chose the control algorithm as follows: if center x < 70, the robot turns right (turn=1); else if center x > 110, the robot turns left (turn=0); else the robot goes straight (flag=0).

Table 3: Recorded center X and contour area with camera setting 320×160, 16 frame/sec

Physical → Meaning	Distance between two robots (cm)	Angle from the camera to the first robot (˚)	Center X recorded from Python program (pixels)	Contour Area recorded from Python program (pixels)
No. Experiments				
1	50	0˚	90 ~ 95	1855 ~ 2280
2	51 ($\sqrt{50^2+20^2}$)	-atan (2/5) = -22˚ (CCW from the camera)	188.5 ~ 200.5	500 ~ 1780
3	51 ($\sqrt{50^2+20^2}$)	atan (2/5) = 22˚ (CW from the camera)	-19.5 ~ -15.5	1750 ~ 2133
4	40	0˚	83 ~ 86	1400 ~ 3700
5	60	0˚	84 ~ 88	987 ~ 1323

(3) Flowchart of programs on both Cortex controller and Raspberry Pi 3 for the tracking robot

According to the flowchart shown in Figure 13 (Abbreviation words can be referred in the bottom of the figure.), the Cortex controller is a master processor. It requires Raspberry Pi continually provide 3-bit data, which are (1) Found (the target is found or not); (2) Flag (the robot needs to turn or not); (3) Turn direction (if it's turning right or left, turn=1 or 0). Based on the three-bit information plus the ultrasonic sensor information, the tracking robot decides to go forward, stop, turn left/right with radius or just turn right/left (without radius) to search the lost target.



Pin Layout: (Name: Cortex, PI): (Found: digital 12, GPIO 26), (Turn: digital 11, GPIO 19), (Flag: digital 10, GPIO 13)
Symbols: D: distance; TL/RO(R): Turn Left/Right at Origin (with Radius); SPW: Speed Power; R/LB: Right/Left Boundary

Figure 13: Program in ROBOTC (for Cortex) and Python (for Raspberry Pi), Respectively

(4) Wire two boards as well as motors and ultrasonic sensors

Figure 14 shows the circuit connection between two processor boards, motors and ultrasonic sensors. Notice that the two boards must share the common ground. Otherwise, the measured signals will be floated.

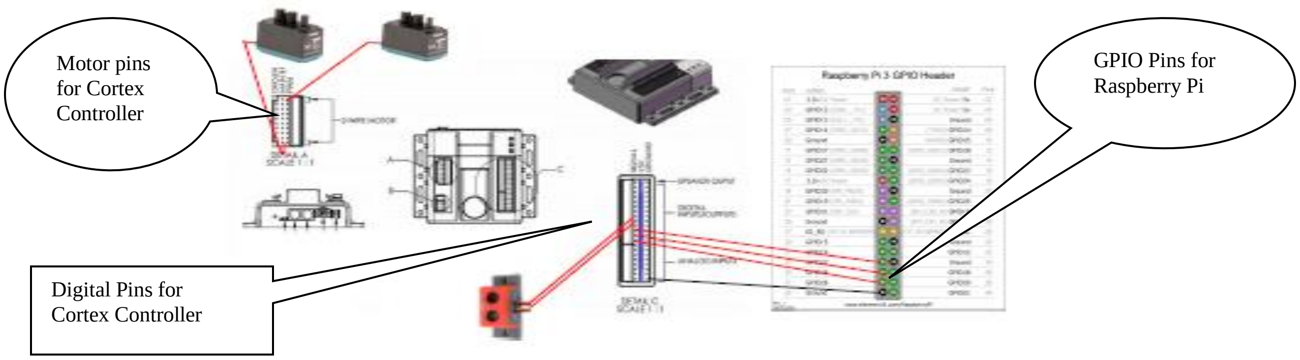

Motor pins for Cortex Controller
GPIO Pins for Raspberry Pi
Digital Pins for Cortex Controller
Raspberry Pi 3 GPIO Header

Figure 14: Hardware Wiring

After the hardware was connected, the system was run by firstly turning on the Raspberry Pi program. When the Raspberry Pi board run well, two Cortex Controllers were turned on.

(5) Laboratory practice

Based on the lecture and building of teaming robots, students were guided to program the PIC microcontroller 18F4580 on the E-block multi-programmer board [10]. The PIC microcontroller board was connected to an LED board, a switch board and a speaker module. The RD0 pin of PIC microcontroller was connected to the GPIO Pin 26 on the Raspberry Pi 3. When the Pi Camera installed on Raspberry Pi 3 detects any change in the environment, such as a person blinks his/her eyes or open his/her mouse, the Raspberry Pi 3 sends a signal to RD0 pin on the PIC board. The PIC microcontroller then flashes LEDs on the LED board and emits a siren sound to the speaker. Figure 15 shows the devices used in the lab. In terms of the programming environment, the PIC microcontroller was programmed in embedded C using the MPLAB X IDE under Windows and the Raspberry Pi 3 was programmed in Python under Debian Operation System.

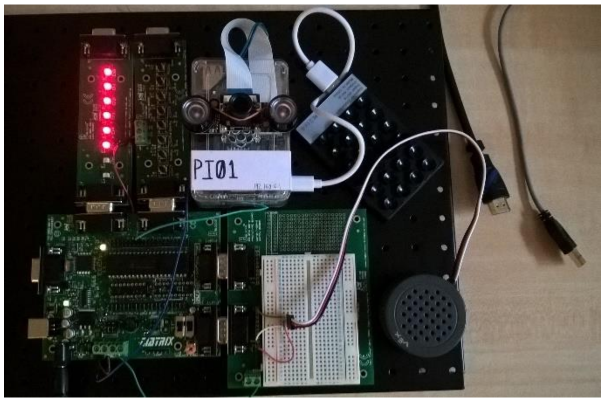


Figure 15: Laboratory Device for the Exercise

5. Student learning results, comments and discussions

The lecture was composed of a power point presentation and the demonstration of building teaming-robots. Students were also briefly taught the fundamental architecture of Raspberry Pi 3 processor since the lecture was arranged by the 13th week in Microprocessors course where students had learned PIC Microcontrollers and embedded C programming. After it, the essential concept of image processing and basic Python program were discussed in comparison with the PIC embedded C program. Before the class were taught, students were provided a 10-question survey. The questions were multiple choices with emphasis on Python and image processing (See the appendix for detail).

Ten students attended the class and 60% of them scored over 60 points. The distribution of the grades is 80%, 80%, 70%, 70%, 60%, 60%, 40%, $40%, 30% and 30%. It can be seen that although all of them hadn't learned Python language, the knowledge that they learned from other computer languages such as C++, embedded and Matlab helped them to find the correct solutions. After the lecture, all students reached 100 points for the problems in question.

For the post-class comments, students wrote:

- Very interesting, I wish we learn more in depth about computer vision and image processing.
- Good better than the fundamental C++ class.
- After the lecture, I would like to learn more about the different applications Python has. Also that it is used for. Maybe have a course to learn Python.
- More information about Python (more lectures) and get a chance to write more codes.
- Good introduction of computer vision and basic Python.
- I would like to see more applications.
- I think it was very interesting. I wish it was more than just one lecture because it seems like this is the direction the industry is going. More computer vision less sensors.
- I think this class should be incorporated into the engineering program, Python.
- I have never practiced Python before, the lecture was pretty informative but now I want to know more, will definitely try what was given for practice with the program online.

Discussion: As college professors, we consider that our mission is to ignite the spark of passion, creativity and energy inherent in our students so that they can believe in their gifts, gain confidence and explore how they will contribute to the world. The idea of teaching engineering design using cross-platform software and hardware is just an approach of inspiring students to develop exciting projects in different levels of classes or areas, even in their club activities and their summer jobs. Here are several examples:

- Freshmen Level – Introduction to Robotics: Although students are not able to use two different microcontrollers or various software design environments, they still can build two robots so that the robots can talk via a bump sensor and an ultrasonic sensor. Thus, the robots can co-work together to complete a duty. Figure 16 shows a course project where freshmen students developed a clunker robot and a butler robot. Two of them talked to each other to complete the duties such as garbage collection, garbage storage and garbage dumping, etc.

- Junior Level – Microprocessors: A group of students was doing a course project: program a Bluetooth board so that their smart phone can talk to a PIC18F4580 microcontroller. However, they didn't have any information to initialize the Bluetooth board. Fortunately, the manufacturer provided the machine code running under a flowcode environment with a midrange PIC microcontroller. Then, students ingeniously initialize the Bluetooth board using a midrange PIC microcontroller and the flowcode environment. After the initialization, they used the Bluetooth board for the advanced 8-bit microcontroller PIC18F4580 under MPLAB X IDE programming environment for their course project. This is another example for the application using cross-platforms for the development of computer hardware and software.

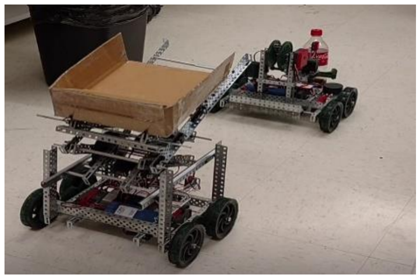
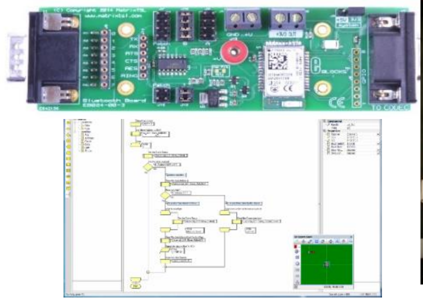
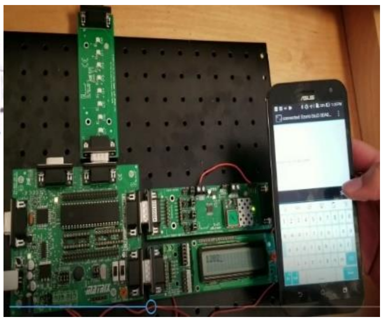
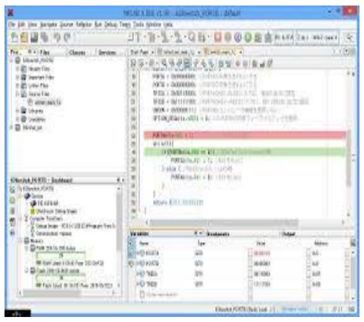


Figure 16: Clunker and Butler Robots

(a) (b) (c)

Figure 16: Cross-Platform Applications for Bluetooth Initialization and Applications
(a) Flowcode with Bluetooth Board; (b) Students' Project; (c) MPLAB X IDE Environment

- Senior Level – Industrial Manufacturing and Automation: A course project is to interconnect a particle photon microcontroller and a storage station controlled by Siemens S300 PLC. A particle photon is a tiny Wi-Fi enabled microcontroller which can be remotely accessed and programed. Through the project, students learned how to conduct the cross-platform design among a Siemens PLC, an embedded controller and a web server. Figure 17 shows the components of the project.

6. Conclusions

In this paper, we presented the motivation and courseware development related to multiple sensors for teaming robots and motion detection using cross platform hardware and software to enhance college students' capability of adopting new technologies in the industry. We believe it's also an excellent approach for students to integrate their knowledge to solve the problems in the real world.

Future improvements include (1) developing more opportunities for students to learn Python, image processing as well as the fundamental knowledge of artificial intelligence so that they can solve more practical engineering problems and (2) creating more exercises for students to do exercises related to cross-platform hardware and software.

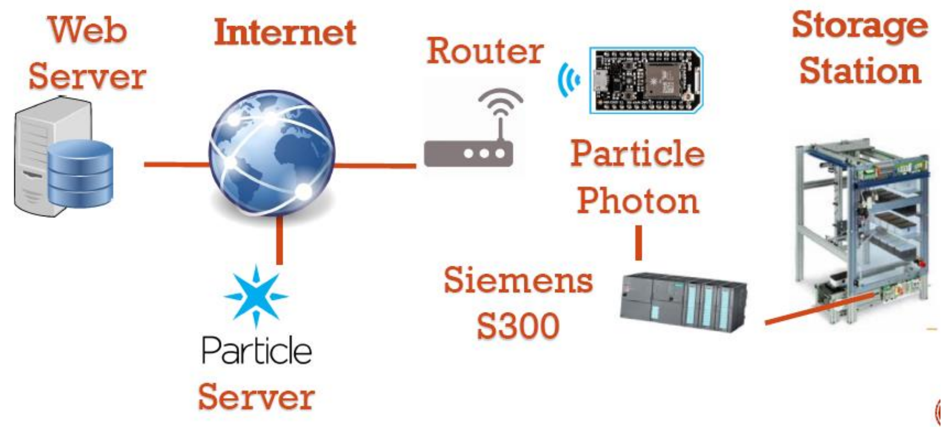


Figure 17: Cross-platform Design among a PLC, a Microcontroller and a Web Server

7. Acknowledgement

The work was supported by a grant from the National Science Foundation's Research Experience for Teachers (RET) Program (Award No. 1300779). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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Appendix - Pre/Post-Class Assessment

1. What are two of the most important benefits of the Python language?

   A. Advanced mathematical equations and fast programs
   B. Ease of use and fast programs
   C. Ease of use and portability
   D. Fast programs and smaller programs

2. What is the correct sequence of steps invoked by the Python Interpreter:

   A. source code → virtual machine → byte code → compiler
   B. source code → compiler → byte code → virtual machine
   C. compiler → source code → virtual machine → byte code
   D. byte code → virtual machine → source code → compiler

3. What is wrong with the following code snippet:

```
num1 = 10
num2 = 20
num3 = 30
total = Num1 + Num2 + Num3
```

   A. Nothing, the variable `total` will be the sum of the three numbers
   B. Python is case sensitive so `Num1`, `Num2`, and `Num3` are undefined
   C. `total` must be initialized to zero first
   D. The numbers should be `10.0, 20.0` and `30.0`

4. What is wrong with the following code snippet?

```
print("Hello")
   print("World!")
```

   A. The print function cannot be called twice
   B. The print function is missing an argument
   C. Nothing, the program prints Hello World on the same line
   D. The second line should not be indented

5. What is the purpose of the following algorithm, written in pseudo-code?

```
num = 0
Repeat the following steps 15 times
    Ask user for next number
    If userNum > num
        num = userNum
Print num
```

   A. To print out the 15 numbers
   B. To find the smallest among 15 numbers
   C. To search for a particular number among 15 numbers
   D. To find the highest among 15 numbers

6. Which of the following statements correctly defines a function?

   A. def functionName(parameterName1, parameterName2) :
   B. def functionName(parameterName1, parameterName2)
   C. functionName(parameterName1, parameterName2) :
   D. functionName(parameterName1, parameterName2)

7. What Python statement exits a function and gives the result to the caller?

   A. def
   B. return
   C. send
   D. result

8. A digital image is a collection of __________ arranged in a grid of rows and columns.

   A. canvases
   B. dots
   C. elementary elements
   D. pixels

9. In an RGB color model, what color is represented by 255, 255, 255?

   A. black
   B. green
   C. white
   D. yellow

10. The difference is intensity between the highest and lowest intensity levels in an image is

    A. noise
    B. saturation
    C. contrast
    D. brightness

Please provide comments for your overall learning experience through the lecture and laboratory activities so that we can continually improve the course module and make it better.