2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
Paper ID #39637

Development of a Raspberry PI-Controlled VEX Robot for a Robotics Technology Course

Dr. Lili Ma, New York City College of Technology

Professor Lili Ma received her Ph.D. in Electrical Engineering from Utah State University focusing on autonomous ground vehicles. After that she did three-year post-doctoral training at Virginia Tech working with unmanned aerial vehicles (UAVs). Prior to joining the Dept. of Computer Engineering Technology at CUNY New York City College of Technology, she taught at Wentworth Institute of Technology for many years. Her research interests are in designing coordinated control schemes for a group of autonomous robots. Her teaching interests are in designing robotic projects that promote undergraduate research and integrate interdisciplinary areas (robotics, artificial intelligence, IoT, electronics, and image processing).

Justin Bartholomew, New York City College of Technology

Justin Bartholomew is a senior student in the department of Computer Engineering Technology (CET) at CUNY-New York City College of Technology. He is interested in circuit design, embedded systems, robotics, artificial intelligence, and Internet of Things (IoT). Justin is currently working as an undergraduate research assistant on an NSF collaborative research project "CISE-MSI: DP: CNS: An Edge-Based Approach to Robust Multi-Robot Systems in Dynamic Environments".

Dr. Yu Wang, New York City College of Technology

Dr. Yu Wang received her Ph.D. degree in Electrical Engineering from the Graduate Center of the City University of New York in 2009. She is an associate professor in the Department of Computer Engineering Technology at New York City College of Technology. Her research areas of interest are engineering education, biomedical sensors, modeling real-time systems, embedded system design, and machine learning.

Dr. Xiaohai Li, New York City College of Technology

Xiaohai Li received his M.S. degree in Electrical Engineering from Polytechnic Institute of New York University, New York, in 2004 and Ph.D. degree in Electrical Engineering from the Graduate Center of the City University of New York, New York, in 2010. He worked as a Post-doc in the PRISM Research Center in the Department of Electrical Engineering at the City College of New York in 2010. He is currently an Associate Professor in the Department of Compute Engineering Technology at NYC College of Technology of the City University of New York (CUNY). He founded the City Tech Robotics Research Lab and is a co-founder of the City Tech Experiential Arts and Technology Lab (EAT Lab) at NYC College of Technology of CUNY. His current research interests include applied control systems, robotics, swarms, wireless sensor networks, computer vision and perceptual computing, and IoT/IoRT.

Development of a Raspberry PI-Controlled VEX Robot for a Robotics Technology Course

Abstract

This paper describes the development of a Raspberry PI-controlled VEX robot for an undergraduate robotic course. The Raspberry PI controls the mobile base built using the VEX robotics kit without using the Cortex microcontroller that comes with the kit. The aim is to create a physical robot that is manageable, easily replicable, and capable of performing advanced robotic control tasks such as vision-based control.

The constructed robot adopts the great features of the PI and the VEX hardware. Firstly, the VEX hardware consists of various sensors and actuators for students to practice the construction and assembly of an autonomous robot. Secondly, the Raspberry PI provides a Linux environment for programming and implementing advanced algorithms. As a result, the robot can assist effective teaching of many STEM subjects involving robotics, image processing, and artificial intelligence. It can also facilitate undergraduate research outside of the classroom.

The paper describes the development of the PI-controlled VEX robot, providing details of its construction, electronics wiring, low-level motion control, onboard image processing, and closed-loop vision-based control.

Introduction

The VEX robotic kits have been adopted widely in undergraduate robotics curricula. The kit contains various mechanical components, sensors, actuators, and a microcontroller (Cortex). The kit provides instructions to build a mobile robot with a simple arm on top. Using this kit, students can go through the process of construction, electronics assembly, and programming. The VEX robot has been used to implement waypoint navigation, map building, and path planning [1].

However, VEX robots primarily focus on motion control and low-level sensing, and they do not have a vision sensor (such as a CCD camera). As a result, it does not provide an onboard image processing capability. In recent years, cameras have become more widely used on robots, allowing a representation of the robot's environment to be acquired through visual input. The limitation of not having the onboard capability to process images prohibits the VEX kits from being used in more advanced robotic applications such as vision-based control.

The department of Computer Engineering Technology (CET) offers "CET 4952: Robotics Technology" [1, 2] as a technical elective to its students in the CET baccalaureate program. The course is structured to have a 3-hour lecture session and a 3-hour lab session each week. It is offered twice a year in both fall and spring semesters. Its course learning objective is to address fundamental subjects in both Autonomous Mobile Robots and Robotic Manipulators, as well as preparing students with necessary knowledge and skills in robotic programming, design, and system integration. Theories and algorithms such as waypoint navigation, map building, obstacle avoidance, and trajectory generation are discussed in the lecture sessions, while lab sessions focus on the application of this knowledge using physical robots [1, 2].

When labs were conducted in traditional face-to-face classrooms, students were asked to complete three projects over one semester. Project-based learning [3] was used in the first two projects to guide students through fundamental algorithms. Inquiry-based learning, a highly self-directed approach of learning and discovering through exploration or observation, was used in the final project, where students apply acquired skills to solve questions independently (with the least amount of help from the instructor). To make the third project (i.e., the final project) more manageable for students, students were given with specified options (candidate projects) and allowed to select one that aligned with their interests. These candidate projects include "vision-based control", "coordinated control", and "MATLAB image processing for depth recovery", to name a few.

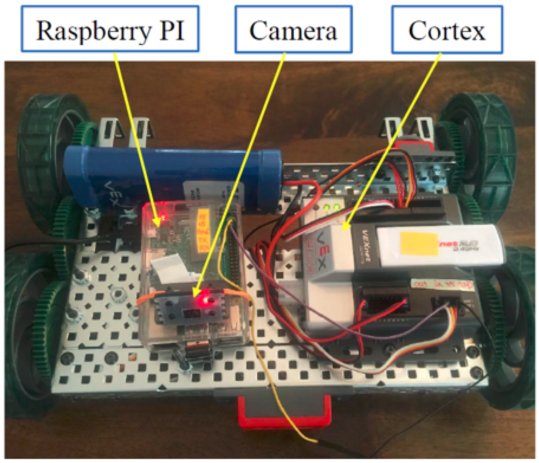
The pandemic urged us to focus on computer-based simulation projects in the past two years [2], but recent requests for more in-person activities have driven expansion of physical experiments. In one project mentioned above, i.e., the vision-based control of Raspberry PI-enhanced VEX robot, the Raspberry PI was integrated with a standard VEX robot (consisting of a mobile base and its micro-controller, the Cortex). The Cortex controls the robot's basic motion, while the Raspberry PI handles image processing and high-level decision making. Commands such as "turning to the left", "going straight", and "turning to the right" were sent from the PI to the Cortes for execution.

This paper describes vision-based control of a PI-controlled VEX robot. This new version does not include the Cortex. The VEX mobile base was controlled directly/solely by the Raspberry PI. In other words, there is only one "brain", i.e., the Raspberry PI [Fig. 1 (b)]. While in the previous version, there are two "brains": the PI and the Cortex [Fig. 1 (a)]. This development addressed one direction of further investigations listed in our earlier paper, by using the Raspberry PI to control the VEX base directly [1]. Reducing the "brains" from two to one resulted in a less complex robot, which is more friendly to the undergraduate students. It also made it easy for other educators to incorporate this hardware/software system into their courses/labs.

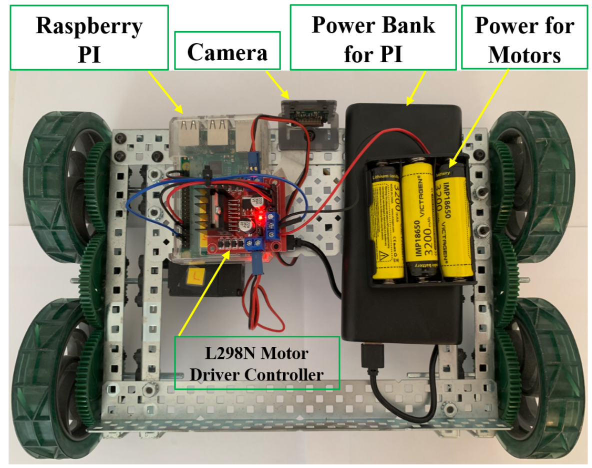
Using the L298N Motor Driver Controller Board, we successfully controlled the two motors to run in different directions, achieving low-level motion control of the robot. With the help of OpenCV libraries, we have achieved onboard image processing for the PI camera using C++. The closed-loop vision-based control is demonstrated via visual servoing the robot to a static target.

Hardware Construction

The PI-controlled VEX robot is constructed using the following components: a mobile base built using the VEX robotic kit; a Raspberry PI microprocessor with its camera module; a L298N motor



(a) The Previous Version: PI-Enhanced VEX Robot



(b) The Newer Version: PI-Controlled VEX Robot

Figure 1: Robots used for vision-based control.

driver controller board; power bank providing power to the PI; batteries providing power to the L298N motor board. The complete part list is given in Fig. 2. Notice that pictures of these parts are copied from their Amazon sales pages.

Excluding the cost of the VEX mobile base, the total cost of the rest of the components is roughly $232.00. We already have several sets of VEX robots for this course, so adding this project is not too costly. There is even a possibility that some students may want to use their own Raspberry PI. The instructor will assist them in installing the necessary libraries on their PI. The knowledge can then be applied outside of the robotics course (projects in other courses and/or undergraduate research investigations).

The VEX mobile base is built simply following the instructions provided by the VEX company. These construction steps are not repeated here. Next, we focus on the wiring associated with the PI, motor board, and their batteries [Fig. 3].

First of all, the ground of the PI and the ground of the motor board need to be connected to have a common ground. Secondly, we connected the GPIO 19 and GPIO 26 pins of the PI to the IN4 and IN3 of the motor board. The GPIO 17 and GPIO 18 pins of the PI are connected to the IN1 and IN2 pins of the motor board. We used three 3.7 V 18650 rechargeable batteries to provide power for the motor board. Its positive and negative leads are connected to the 12V and GND pins of the motor board, respectively. The two VEX 393 motors that drive the mobile base are then connected to OUT 1, 2 and OUT 3, 4, respectively. During testing and debugging, the Raspberry PI is powered by its power supply. For autonomous operations, a portable power bank is used to provide power to the PI. The power bank and the PI is connected via a USB to Micro USB cable, which comes with the power bank. The connections between the PI and the motor board via the male-to-male cables are very secure with little to no movement or loosening. Overall, these connections are straightforward and easy to understand for undergraduate students.

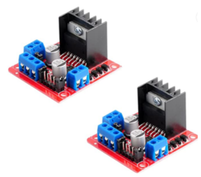
Raspberry PI plus its Camera Module	L298N Motor Driver Controller Board	Portable Power Bank (Providing Power to the PI)	Rechargeable Batteries and Charger	QTEATAK 8 Pack 18650 Battery Holder Bundle	Several Female-Female/Male Cables
 We are using Raspberry PI 3 Model B. Clearly newer versions of the PI will work too.	 Two boards for roughly $8.00. So, $4.00 for one.	 Cable is provided connects to the PI directly.	 18650 Battery Charger Combo 3.7V	 We only used the one with 3 battery slots.	We used 4 female-female cables and 1 male-female cable.
$150.00 for both	$4.00/each	$30.00	$38.00	$10.00	Negligible
				Total Cost (Excluding the Mobile Base)	**$232.00**

Figure 2: List of parts.

Software Programming

Regarding programming language, C++ and Python are generally the two most widely used languages on the Raspberry PI. Between these two, currently we used C++ (due to the instructor's own programming skills) and downloaded Code::Blocks [4] as the editor. In the future, we are interested in exploring the Python programming language to provide useful guidance to students no matter which language they prefer (C++ or Python).

After the physical robot has been constructed, programming and control of the robot includes a) control of the motors (i.e., low-level motion control that requires the WiringPi library [5]); b) image processing to obtain visual clues from the environment (i.e., feature extraction that requires the OpenCV libraries [6]); and c) closed-loop vision-based control where the visual clues are used to control the behavior of the robot (i.e., visual servoing [7]). These modules are described next.

Low-Level Motion Control: Interfacing Raspberry PI with one L298N Motor Driver Module allows control of two DC motors. The mobile base in Fig. 1 was constructed using two VEX 393 motors that are the primary motors used for robot mechanisms. These two motors spin the wheels on either side of the robot. The WiringPi library [5], i.e., the GPIO Interface library for the Raspberry Pi, needs to be installed. For the wiring described earlier, in the C++ program, the connections between the PI GPIO pins and the L298N pins need to be initialized. The rest of the motor control task is done by C++ programming, including commanding the motors to move forward or backward. The C++ program is shown below as file name zTest1.cpp. The generated executable file is zTest1 and can be executed by "sudo ./zTest1".

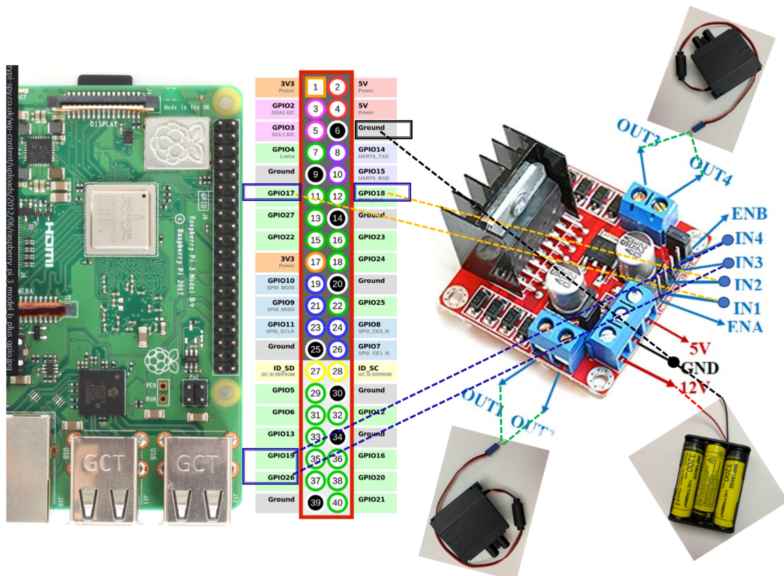


Figure 3: Wiring among the PI, the motor board, and their batteries.

```
pi@pi:~/Lili $ g++ -ggdb zTest1.cpp -o zTest1 -lwiringPi -std=c++0x
pi@pi:~/Lili $ sudo ./zTest1
```

Onboard Image Processing: In the lecture session of the robotic course, we have Incorporated an introduction to image processing, briefly covering topics such as color space, filtering for noise reduction, color-based feature extraction, and Hough transform for line and circle detection. Typical steps in the color-based feature extraction routine include:

- Color space conversion from RGB (Red-Green-Blue) to HSV (Hue-Saturation-Value).
- Thresholding the HUE Image based on user-specified lower and upper bounds.
- Applying filter for noise removal/reduction.
- Finding the largest connected region based on the area or contour points.
- Post-processing to find features such as center and area.

These steps were taken when trying to extract the center of a red object using Raspberry PI's camera. The command-line compiling of the C++ program that integrates both image processing and motor control is shown below:

```
pi@pi:~/Lili $ g++ -ggdb zTest2.cpp -o zTest2 `pkg-config --cflags --libs
 opencv` -lwiringPi -std=c++0x
pi@pi:~/Lili $ sudo ./zTest2
```

Closed-Loop Vision-Based Control: A visual servoing task is to command an autonomous mobile robot to approach a target (with assumed known pattern) certain distance away. For a quick verification that the constructed robot is capable of performing closed-loop vision-based control tasks, we selected a very simple target, i.e., a small piece of red paper. The background is made clean to reduce miss/false detection. The control objective is to command the robot to stop when it gets too close to the target. Since the robot is controlled based on visual hints, the actual logic associated with moving forward or stopping is based on the detected area of the target. If this area is larger than a pre-specified value (for example, we used 900 in pixel coordinates), then the robot will be commanded to stop.

Figures 4 and 5 show two runs of the visual servoing task. The robot started from approximately 4.5 feet away from the target in Fig. 4, and from 7 feet away in Fig. 5. In both cases, the robot stopped when the detected area of the target is bigger than the specified threshold. The picture on the left shows the image processing results on the Raspberry PI. The pictures on the right provide several snapshots of the robot's movement. To improve the image processing speed, images captured by the PI camera are resized to be $1/4$ of its original dimension.

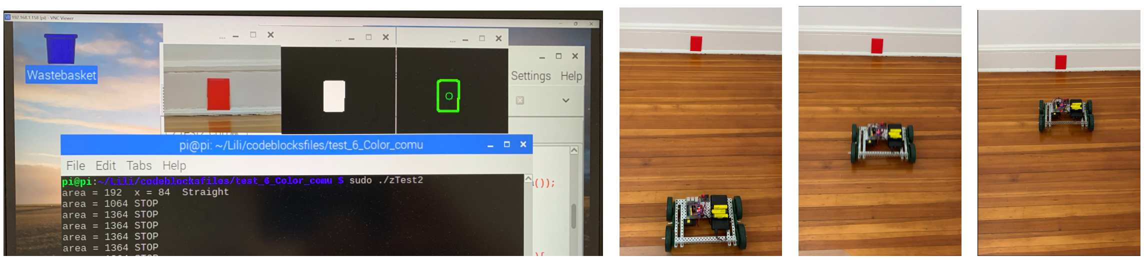


Figure 4: Visual servoing to a red object – Run #1.

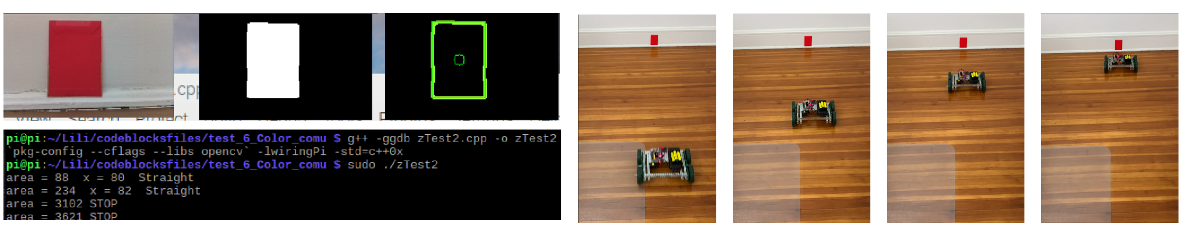


Figure 5: Visual servoing to a red object – Run #2.

We have demonstrated that the constructed Raspberry PI-controlled VEX robot is capable of performing closed-loop vision-based control tasks. This makes the robot suitable for more complicated tasks.

Inclusion in the Robotics Technology Course

The motivation of this work is to continue developing/refining projects used in an undergraduate robotic course "CET 4952: Robotics Technology". In the lecture sessions, fundamental subjects in autonomous mobile robots and robotic manipulators are discussed. Students completed three projects in the lab sessions, including one on autonomous mobile robots, one on robotic manipulators, and one on advanced robotic control. These three projects were designed with increasing complexity. Project 1 prepares students to obtain basic understanding and programming experience. Students will then acquire more solid programming skills in Project 2. Project 3 eventually exposes students to real-world software design and algorithm implementation. Step by step, students will acquire the knowledge, skills, and experience of designing and implementing algorithms for robotic applications.

To accommodate students' interests, we provide several options (candidate projects) to the students for Project 3. Students are allowed to select one among the given options, including:

- Software-driven projects such as "Depth recovery using the MATLAB Image Acquisition Toolbox and the Image Processing Toolbox".
- Electronics-driven project where the students explore the usage of several other sensors that were not elaborated/used before.
- IoT-driven projects where students integrated IoT (Internet of Things) with the VEX robot so that the robot can be commanded from the students' cellphone or another laptop.
- Visual servoing/tracking projects using the Raspberry PI-enhanced VEX robot (the previous version) where the Raspberry PI was added to communicate with the VEX Cortex.

The PI-controlled robot is a newer version of the PI-enhanced robot. Thus, it can be adopted into the lab sessions of the robotic course right away.

Impact of the Change on the Course and Students

This newer version provides students with a platform for C++ or Python programming in the Linux Operating System, which is a significant step forward compared with the RobotC programming on the VEX's microcontroller as done previously. By doing image processing via the OpenCV libraries, students have the opportunity to perform serious algorithm development. They now have to consider physical hardware limitations such as processing speed.

The impact and significance go beyond the robotic course. Removing the VEX micro-controller Cortex yields a **decoupling** in the robot's "brain" and its "motion-execution-system" (i.e., the mobile base). The "brain" (consisting of the Raspberry PI, its camera module, the L298N motor board, and the associated batteries) can be easily duplicated/replicated and is compatible with other motion-execution systems. This decoupling allows the students to continue their investigations in future activities (design projects, undergraduate research) outside the robotic course. We believe the developed robot will help to achieve the ultimate goal of education, i.e., promoting the acquiring, continuation, and application of knowledge through life-long learning.

Conclusions and Future Work

This paper describes the development of a Raspberry PI-controlled VEX robot that can be used as the physical platform for advanced robotic control tasks such as vision-based control. This robot is built using the Raspberry PI, its camera module, a L298N motor board, and a mobile base constructed using the mechanical parts provided in a VEX robotic kit. Intended as the final project in an undergraduate robotic course, this project walks students through hardware assembly, electronics wiring, low-level motion control, image processing, C++ programming, operations on Linux, and vision-based control. This project can also integrate other STEM subjects including Internet of Things (IoT), Image Processing, and Artificial Intelligence, initiating course-level collaborations.

Results presented in this paper proved the capability of the Raspberry PI-controlled VEX robot for advanced robotic control tasks. Future investigations will seek development in several directions, including a) improvement of the low-level motion control; b) programming in Python; and c) exploration of ROS [8–10] on the PI for robustness and scalability.

References

[1] L. Ma, "Teaching undergraduate robotic courses using enhanced VEX robots," *Journal of STEM Education: Innovations and Research*, vol. 22, July-September 2021.

[2] L. Ma, Y. Wang, C. Xu, and X. Li, "Online robotics technology course design by balancing workload and affect," *Transactions of the SDPS: Journal of Integrated Design and Process Science*, January 2022.

[3] E. Fini, F. Awadallah, M. Parast, and T. Abu-Lebdeh, "The impact of project-based learning on improving student learning outcomes of sustainability concepts in transportation engineering courses," *European Journal of Engineering Education*, vol. 43, 2018.

[4] "Code::Blocks," [Online] https://www.codeblocks.org/.

[5] "Wiring Pi," [Online] http://wiringpi.com/.

[6] "OpenCV," [Online] https://opencv.org/.

[7] M. D. Berkemeier and L. Ma, "Visual servoing of an omnidirectional mobile robot to parking lot lines," *International Journal of Robotics and Automation*, vol. 29, pp. 67–80, 2014.

[8] J. Canas, E. Perdices, L. Garcia-Perez, and J. Fernandez-Conde, "A ROS-based open tool for intelligent robotics education," *Applied Sciences*, vol. 10, 2020.

[9] S. Wilkerson, J. Forsyth, C. Sperbeck, M. Jones, and P. Lynn, "A student project using robotic operating system (ROS) for undergraduate research," in *ASEE Annual Conference & Exposition*, 2017.

[10] K. Khan, "ROS-based control of a manipulator arm for balancing a ball on a plate," in *ASEE Annual Conference and Exposition*, 2017.