

Autonomous Robot Design and Build: Novel Hands-on Experience for Undergraduate Students

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Abstract

Using autonomous educational robots in a microcontroller-based course is not a novel idea anymore. But novelty comes when one of the two things happen namely: (i) Designing cost-effective autonomous educational robots using budget constraints and (ii) Having your undergraduate students experience the entire design process when building the autonomous educational robots by themselves. We at Grand Valley State University combine both the aforementioned aspect of building robots. This not only provides a true hands-on design and build experience for undergraduate students working under budget constraints but also instills into them a sense of ownership for the final product.

The paper first talks about the need to develop the autonomous robot, the budget constraints and the limited resources available to design the robots. Next, we talk about several phases involved in building a product starting from brainstorming session, prototype revisions, component selection to milling the board, placing the components to writing software to control the robots. With a limited budget on hand, two students who were assigned the task to build the robot had to re-iterate on certain phases of the development cycle to make sure that do not go over the budget and still develop the final working version of the robot.

Later, in the paper we talk about the sense of ownership imparted to the two undergraduate students to be responsible for the final product. Since the autonomous robot had to be utilized in the sophomore-level Digital Systems course laboratory, these undergraduate students were also assigned the task of developing laboratory exercises to be used in the course. This gave those students a chance to thoroughly test their design, debug if necessary and document their work properly. Finally, we conclude the paper with lessons learned and ideas for improving the design to build experience gained by the undergraduate students.

I. Introduction

Traditionally, microcontroller courses in academia have been taught by concentrating mainly on the architecture and ways of programming these devices with very little exposure to real-world applications. The new trend is to take this setting beyond the traditional classroom teaching and expose students to a dynamic teaching approach where they can explore real-world problems and challenges. Many universities have started implementing this new educational approach called as *Project Based Learning*¹ (PBL) in their curriculum. One of the primary benefits of PBL is that it

combines traditional classroom knowledge with real-world expertise to better prepare students for success.

With microcontroller-based sensing and control becoming inevitable in almost every field, many universities have started using educational robots^{2,3} in teaching microcontroller fundamentals to the students. Thus educational robots have become the primary candidate for hands-on and constructive learning. With this being said, using autonomous educational robots in a microcontroller-based course is not a novel idea anymore. But novelty comes when one of the two things happen namely: (i) Designing cost-effective autonomous educational robots using budget constraints and (ii) Having your undergraduate students experience the entire design process when building the autonomous educational robots by themselves.

Two undergraduate students were assigned the task of designing and building the autonomous robots that would be used in the Introductory Digital Systems course laboratory by the students taking the course. There were two criteria that the students had to meet namely, (i) exhibit interest in building the robot and (ii) already taken the introductory microcontroller programming and circuit analysis course in the prior semester. The first criterion was required so that the students would deliver a working version of the robot under faculty supervision because of their arduous interest. The second criterion was important so that students had basic knowledge about microcontroller programming, interfacing and circuit analysis to instantly begin working on the design.

Faculty in School of Engineering at Grand Valley State University has combined both the aforementioned aspect of building robots and supervised two undergraduate students to design and build the robots. This not only provides a true hands-on design and build experience for the undergraduate students working under budget constraints but also instills into them a sense of ownership for the final product.

The paper is organized as follows: the next section talks about the need to develop the autonomous robot, the budget constraints and the limited resources available to design the robots. The paper then describes the several phases involved in building the robot. Later, in the paper we talk about the sense of ownership imparted to the two undergraduate students to be responsible for the final product in the form of developing laboratory exercises to be used in the course. This gave those students a chance to thoroughly test their design, debug if necessary and document their work properly. We finally conclude the paper with our concluding remarks.

II. Need

With the advent of PBL technique, an alternative method to teach microcontroller fundamentals came into existence. The approach was to emphasize on learning exercises and hands-on activities. Learning microcontroller theory with real-world applications provides the opportunity of tackling problems which would not be normally encountered in traditional learning. In order to enforce this, the students were required to purchase the Arduino Uno board for the course. The Arduino board⁴ and programming language is an inexpensive way for faculty to teach microcontroller fundamentals in introductory courses.

After taking this first step, we now wanted to come up with a project that would not only be fun and exciting but also add an educational value to the microcontroller learning. That is when I came across two undergraduate students who were working in the engineering laboratory. “*Just for fun*” is what they quote for their hobby time and I saw them remotely driving a sad version of the robot in the hallway. After talking to them, I realized that they had just put together bunch of components such as a small/cheap tank chassis, 435 MHz transceiver pair, two Arduinos, a battery pack from laboratory support and motor driver and were successfully driving the robot in the hallway. This struck me as a perfect project for the Introductory Digital Systems laboratory which would not only be appealing to the students but also challenging at the same time. Many universities have geared towards this approach and have started using or building autonomous robots in their microcontroller course⁵.

Both the students were interested in helping out to design the robots and since they had already taken the introductory digital systems and circuit analysis course, they were familiar with microcontroller programming and circuit layout. Now the question was about funding to cover the component expenses and manufacturing boards. Funds were not readily available on a university budget, so we started applying to grants to cover the expenses. Fortunately, we were able to receive a grant that would cover the expense of few robots and the engineering department readily agreed to match the grant to help us build additional robots.

III. Design and Build Phases

Initially, few brainstorming sessions happened to identify the resources that could be used within the given budget constraint. The idea was to use off-the-shelf components to quickly design a working prototype to validate the proof-of-concept before me moved further. The students were able to dig out an old chassis and due to prior knowledge on using AutoCAD and the availability of 3D printers, they were quickly able to design a working prototype for the robot as shown in Figure 1a below.

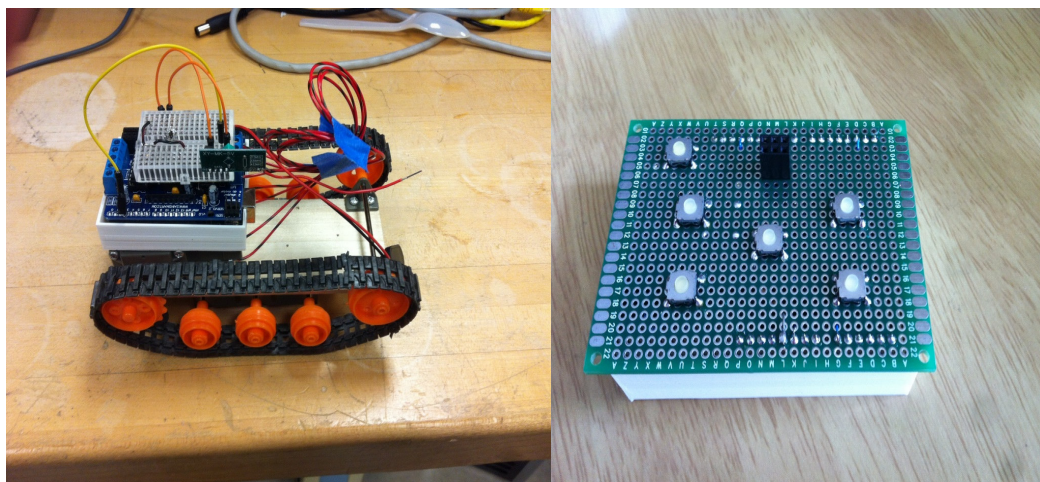


Figure 1 (a and b): Initial prototypes for RF-controller and robot

Now we needed an RF-transmitter to be able to send commands to move the robot. So they designed a *Perfboard* as shown in Figure 1b (material used to prototype electronic components) that would fit onto the Arduino Uno board using the header rails as mounts. A small resistor divider network and a hand full of pushbuttons were utilized to build a circuit that was read by the analog-to-digital converter (ADC) of the Arduino. These ADC values where translated into movement commands and sent to the robot over an RF communication channel to make the robot move in different directions such as forward, backward, etc.

After successful first iteration, it was decided to break the design into two phases. The first phase would be to design and build the transmitter unit while the second would be to build the chassis receiver. During the brainstorming session for the phase one design, it was agreed that the LCD shield should be incorporated into the transmitter controller for an enhanced user experience and for debugging purposes. The challenge that was put forth us was to interface the LCD shield with the RF chip as we had limited I/O ports available on the Arduino board. After extensive research, another hobbyist chip was found called Nordic NRF24L01⁶. This chip used the WIFI band and had an improved range and greater programmer flexibility. Two pairs of these inexpensive chips were bought and experimented with before getting into the circuit design. Another requirement of the controller and the robot was that the student should be able to program them using their own Arduino board allowing anyone with an Arduino board to use the devices.

Once the product specifications were in place, both the students started working on designing a prototype model for enclosure. Students used Solidworks tool to design the prototype that included designing the PCB area, LCD-Arduino-user interfaces to ensure that each piece would fit in the design as intended. Figure 2 below gives you a glimpse of the prototype design drawn in Solidworks that was later printed using the Makerbot 3D printers available on campus.

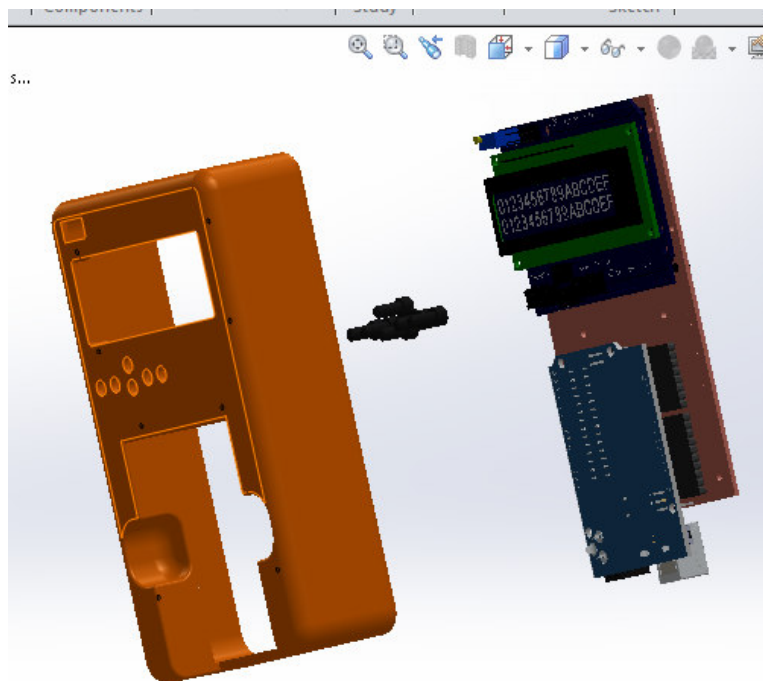


Figure 2: Prototype design drawn using Solidworks

Once the design for the enclosure was finalized, the next step would be to design the circuit that would allow the Arduino to plug into the RF-controller. The circuit (shown in Figure 3a) was first mocked-up using some small breadboards to ensure everything will work together, and to trouble-shoot as much of the hardware ahead of the PCB fabrication as possible. Once the bugs were worked out, a circuit was laid out (shown in Figure 3b) using the Eagle software. The designed circuit allowed the pins of the Arduino to be mapped to the LCD as if the LCD was plugged into the Arduino so the user would not have to worry about pin assignments.

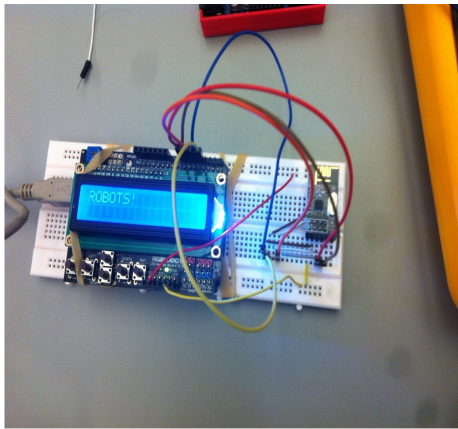


Figure 3a: Breadboard prototype with LCD shield and WIFI breakout board

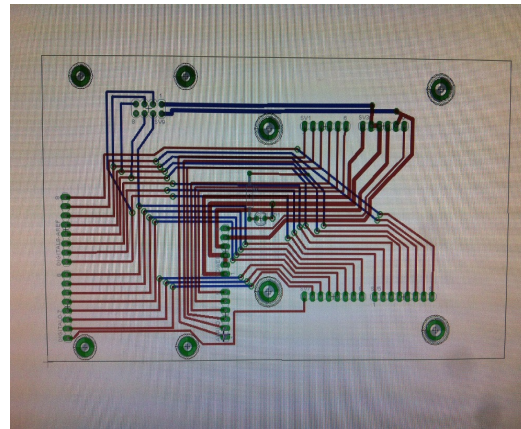


Figure 3b: First prototype of the PCB layout

This layout went through a several iterations to get the final version of PCB printed using the 3D in-house printer and have all the devices fit into their solder mounts. The first iterations of the PCB had square corners that had to be manually filed by hand to fit the round corner design of the housing. Later a work around was discovered in the Eagle software that allowed round corners as well as some cutouts to allow wires to pass from top to bottom, allowing the PCB mill to do the work. After three iterations of the PCB, the final design was ready without any errors.

Putting it all together into a finished design (see Figure 4a) took about four months of working on it during their spare time as they were concurrently taking other classes. Phase 2 of the design process was a little simpler as they had to only design a receiver package that would mount on to the designed enclosure from Phase 1. The receiver package to be mounted on the robot incorporated motor controller, WIFI chip and another add-on shield called the GADGET shield. The GADGET shield was very useful as it had several sensors such as tilt sensor, buzzer, potentiometer, infrared sensor, LEDs etc. It was also decided to build our own battery packs and charging system to complete the custom design. In addition, it was decided to utilize the transmitter enclosure design and modify it as necessary to save on design time. With several revisions, the final design as shown in Figure 4b was made.

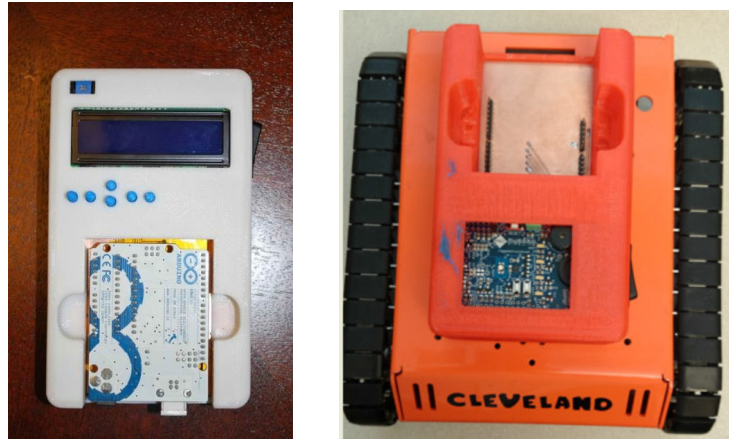


Figure 4 (a and b): RF-LCD Transmitter and RF-robot

The final piece to the puzzle was designing custom battery packs. For this, we chose a small lithium battery control module that would control three batteries in a series configuration. 18650 lithium laptop battery pack cells were chosen to power the chassis motors, and from these size constraints, a battery containment box was designed in Solidworks and printed on the 3D printer.

The two students really appreciated the exposure they received in taking a proof-of-concept on a piece of paper to developing a fully functional end-product with budget constraints. They considered this as a must-win experience for them to be involved in a project like this.

IV. Sample Laboratory Exercises and Project

Once the RF-LCD controller and the RF-enabled robot was build, the next step was to thoroughly test the design to make sure it would work for all possible cases. Thus, both the students were assigned the task of creating laboratory exercises and possibly a project that would be later used in the course during the semester. This gave them the opportunity to test their design, debug the issues if required and properly document their work that could be used by other students for further enhancements.

The following is an outline of the three laboratory assignments and one project that the two undergraduate students developed for the course:

- **Laboratory #1:** The purpose of the laboratory was to teach students to work with GPIO of microcontroller and communicate with Arduino over serial interface. To be able to do this we required students to work with an add-on shield (Gadget shield as shown in Figure 5) that has several peripherals and sensors that students can take advantage of. The Gadget shield has been incorporated into the RF-enabled robot and students were required to work with it and insert their own Arduino into the robot. In this laboratory, students are required to create a Digital Lock program that allows them to work with pushbuttons, LED's and serial interface capability of the microcontroller.

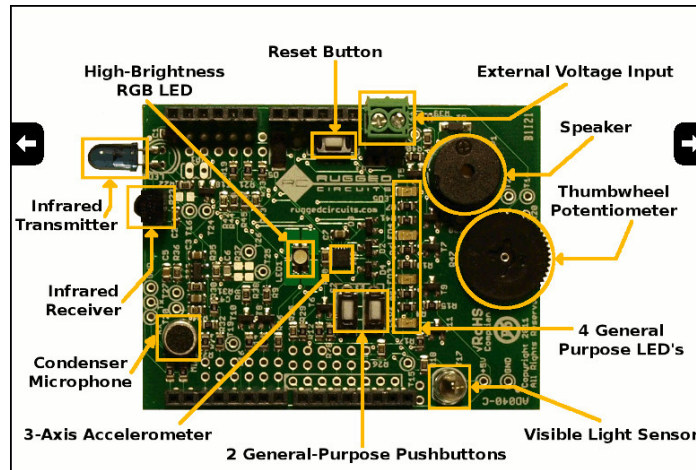


Figure 5: Sensors and actuators on the Gadget Shield

- **Laboratory #2:** The purpose of the laboratory was to teach students to interface Arduino with the LCD. For this laboratory, students were required to work with the RF-LCD controller that has the LCD module embedded in it and students insert their own Arduino board into the controller. In this laboratory, students are required to design Slot Machine game that the user plays with the microcontroller. In this laboratory, students create their own symbols and are allowed to use some of the pre-built functions for random number generation. Sample output of the game is shown in Figure 6 below.



Figure 6: Sample output of Slot Machine (Lose/Win)

- **Laboratory #3:** The purpose of the laboratory was to teach students the principle of pulse-width modulation (PWM). In this laboratory, students work with the autonomous robot and are required to design a menu-driven motor speed control application that varies the speed of the motor on the robot based on user input.
- **Final Project:** The final project is spread over two weeks where students learn about interrupt mechanism and analog-to-digital (A/D) conversion and apply those concepts during the first week of the project. In the second week, students integrate everything together

(knowledge about GPIO's, timers, PWM, interrupts, A/D conversion) to create a working application. The students are given two weeks to design and implement the project by using pre-designed components from the laboratory assignments and/or creating new components from scratch.

With the introduction of RF-LCD controller and the autonomous robot in the previous laboratory exercises, students are required to accomplish RF communication between two RF-LCD controllers during their first week of the project. In the second week, students put the RF-receive code on the robot along with interrupts, A/D conversion and PWM functionality of the microcontroller to move the robot in the maze based on the commands send by the RF-LCD controller (that has the RF-transmit code).

The laboratory exercises and the project was successfully created and used by the students in Winter 2015. We have another paper that talks about the assessment of the course after the introduction of the RF-enabled controller and the robot.

V. Conclusion

The ABET definition of engineering design and build states that *"it is a decision-making process (often iterative), in which the basic sciences and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective."* This is exactly what we made the two undergraduate students experience when designing the controller and the robot. Additionally, we enforced budget constraints on the students and imparted into them a sense of product ownership by making them responsible for developing laboratory exercises and project to be utilized in the introductory digital systems course.

The two students were able to successfully develop a working final product that they duplicated later to be able to use in the laboratory by several students. The robots and the controllers are currently being used by the students in Winter 2015 semester and it has been a huge success. It was a good learning platform for both the students where they went through several phases involved in building a product starting from brainstorming session, prototype revisions, component selection to milling the board, placing the components to writing software to control the robots. Documentation about your product is considered to be one of the weakest links amongst engineering student. So to overcome that weakness, it was required that both the students document their work in form of laboratory exercises and project and they did a fairly good job at it.

This approach seemed to have the right blend of converting an idea on a piece of paper into actual working product and gave students a real-world experience of design and build process that they would undergo in an industry.

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