ELEC 291 Magnetic Field Track Robot

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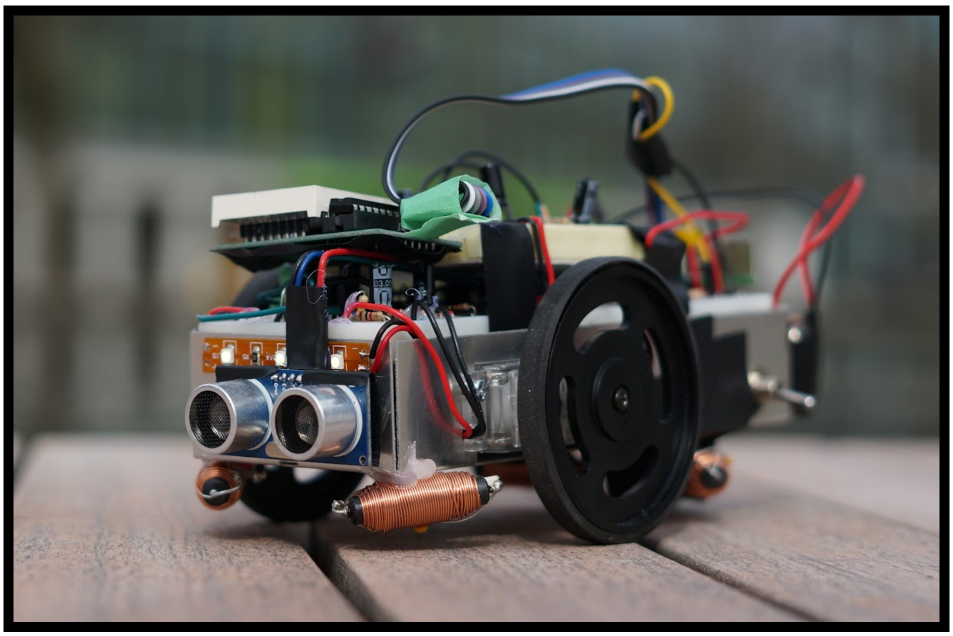

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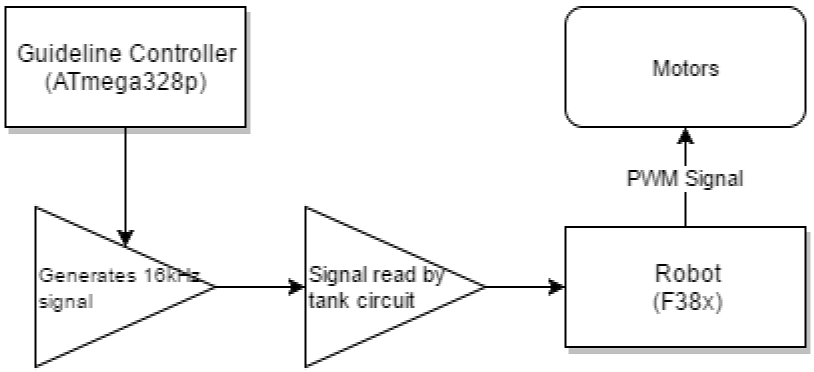
1. INTRODUCTION

Objectives

The objective of this project was to design, build, program, and test an autonomous robot which is controlled using the magnetic field generated by a guide wire.



Specifications

Guide wire frequency:	16kHz
Wire communication baud rate:	15.625 (64.00ms per bit)
Battery life:	~20 minutes - 500mA on 9V battery

Parts List

Microcontrollers

Qty	***Part Number***	***Description***	***Manufacturer***
1	C8051F38C	8051 microcontroller	Silicon Laboratories, Inc.
1	ATMega328P	AVR microcontroller	Atmel Corporation

Robot Assembly

Qty	***Part***	***Manufacturer***
1	Custom waterjet cut aluminum chassis	
2	GM4 Clear servo motor	Solarbotics

2	Servo 2.63" x 0.35" wheel	Lynxmotion
1	70144 ball caster	Tamiya
4	AA battery holder	
1	9V battery clip	

Robot

Qty	***Part Number***	***Description***	***Manufacturer***
1	LTV847	Optocoupler	LiteOn Incorporated
2	LMC7660IN	Switched Capacitor Voltage Converter	National Semiconductor
4	LM358AN	Dual Operational Amplifier	Fairchild Semiconductor
1	L7805CV	Positive Voltage Regulator	STMicroelectronics
2	FQP8P10	P-Channel QFET MOSFET	Fairchild Semiconductor
2	FQP13N06L	N-Channel QFET MOSFET	Fairchild Semiconductor
4	5258-RC	1mH inductor	Bourns Inc.
1	BL-M12X881	Red LED Matrix - 8x8 (32x32mm)	BETLUX
1	LM393N	Comparator	Texas Instruments
1	MAX7219	Serially Interfaced LED Driver	Maxim Integrated
1	HC-SR04	Ultrasonic Ranging Sensor	Sainsmart
4		1µF capacitor	
6	1N4007	General-Purpose Rectifier Diode	Fairchild Semiconductor
4		10µF 50 V capacitor	
4		4.7µF 50 V capacitor	
8		1kΩ 5% tolerance resistor	
4		47kΩ 5% tolerance resistor	
4		33kΩ 5% tolerance resistor	
4		100kΩ 5% tolerance resistor	
2		5mm yellow LED	
1		5cm red LED strip	
1		5cm white LED strip	

Guide Wire Generator

Qty	***Part Number***	***Description***	***Manufacturer***
1	KY-023	Joystick controller	
1	BO230XS	Serial USB adaptor	Jesus Calvino-Fraga
1	ATS16B-E	16.0000MHz CTS Quartz Crystal	CTS
1	SD1602H	LCD	Hitachi
1		1kΩ 5% tolerance resistor	
1		2kΩ 1% tolerance resistor	
1		220Ω 5% tolerance resistor	
2		5mm LED	
3	EVQ-11A04M	Tactile Switch (Pushbutton)	Panasonic

Software Features

Robot Controller

- Reads commands sent through the wire's magnetic field as binary
- Supports Interpretation from binary for:
  - Stop
  - Turn left at the next intersection
  - Turn right at the next intersection
  - Track forward
  - Track backward
  - U-Turn (rotate 180 degrees)
- Sonar System
  - Detects incoming objects and stops

Guide Wire Generator

- Sends Commands to Robot Controller
  - Toggles the 16kHz signal which relays binary code through the wire's magnetic field
- Sends Binary Code for:
  - Stop
  - Turn left at the next intersection
  - Turn right at the next intersection
  - Track forward
  - Track backward
  - U-Turn (rotate 180 degrees)

2. Investigation

Idea Generation

Our team generated ideas by going through the steps of the design process (i.e. identifying requirements and generating multiple ideas that satisfied these requirements). Our decided upon Idea should be the most efficient. In this case, that meant that we wanted our robot to move smoothly, quickly and receive data at the fastest possible frequency.

Ideally, we also wanted designs that were modular, which consist of independent components. This would enable a better workflow because parts of the project would not depend on each other; thus, allowing better communication and collaboration within the team.

Design Investigation

Our team gathered data through online research and testing. We also used the lab tools to gather data, which is expanded on below in *Data Collection.*

Data Collection

Referring to online datasheets when building our potential design, we would test expected outputs using tools provided to us in the lab. Below are some of the ways we used the tools in Macleod Lab:

Multimeter: Used to measure voltages of various components of our circuits-such as the outputs of the op amps[1] and the comparators[2]-and to check the continuity of our circuit prototypes.

Function generator: We used the function generator to generate square waves through our guide wire to simulate a 16kHz signal in order to test our robot.

Oscilloscope: With our capacitance and inductance values; the theoretical resonance frequency was 16kHz. We used the oscilloscope to ensure that this was true.

Power supply: Used to save batteries and to determine the amount of current that was being drawn out of our circuit at certain voltage levels. The power supply was also used to test our design's characteristics, such as the speed of the motors, at different levels of power.

Using the same methods outlined above to analyze potential designs, we tested various circuit components. We used the oscilloscope to read the accuracy of our peak detectors, ensuring that the signal was DC, and to debug the output signals throughout the circuit. We then checked with the multimeter to confirm voltages and frequencies.

Data synthesis

While testing our design, we would observe readings on the oscilloscope and multimeter, values on PuTTy and the physical movement of our robot.

When testing our tank circuits, we would test the outputs before implementing it into our main robot. The most effective way our team tested the tank circuits was to hold the inductor[3] over a wire with current and observe the DC signal displayed on an oscilloscope. From this we observed that the amplitude of the voltage increased very rapidly as the wire was brought closer to the inductor. This was especially apparent as the inductor followed an exponential curve relative to distance, and would increase rapidly as it gets within millimetres of the inductor.

Analysis of Results

Our team appraised the validity of conclusions through the actual execution of our robot. When testing the commands of our robot (forwards, backwards, turns, etc), we agreed with our design when the robot would execute our instructed command throughout a consistent number of test cases. This is explained further in Section 3 under Solution Assessment.

3. Design

Use of Design Process

Using the design process, we generated multiple ideas for potential designs. This gave our team the opportunity to discuss which design we thought would be best for our robot.

Need and Constraint Identification

The needs for the magnetic track robot were outlined according to our lab manual. In addition to these requirements, some of the needs our team identified for customers are stated below:

- ➔ Ease of use: The ability to communicate to the robot through the guide wire should be quick and simple
- ➔ Run smoothly

Constraints of our robot were also outlined in our lab manual (i.e. the controllers operating at a single frequency).

Problem Specification

To increase ease of use, our team implemented an LED matrix[4] that displays the instruction sent to the robot. This allows the user to easily visualize how the robot executes instruction.

Solution Generation

Buttons on guide wire generator to send commands:

To communicate with the robot (i.e send a command to turn left, right, stop, 180 degrees), a potential solution was to install buttons[5] on the guide wire generator; each button sending a specific command when pressed.

Joystick[6] to send commands:

Similarly, we would install a joystick to send commands instead. The direction on the joystick would send the respective command (see Figure 5.1).

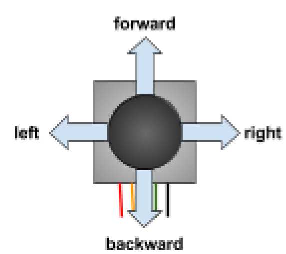


Figure 3.1: Joystick controls

Solution Evaluation

The following tables detail our attempts at different configurations for our inductors as well different methods of PWM for our motors.

Table 3.1: Testing Different Inductor Configurations

Design Concept	**Two (2) Inductors**	**Three (3) Inductors**	**Four (4) Inductors**
Description	Two tank circuits at the front of the robot set at a 45 degree angle	Two inductors parallel to the guide wire and one perpendicular	Two inductors at the front set at a 45 degree angle and two inductors at the back at a 45 degree angle.
Forward Tracking	Accurate	Accurate	Accurate
Reverse Tracking	Inoperative	Inaccurate	Accurate
Intersections	Detects intersections with inductors on a 45 degree angle Navigates intersections with high error Trouble understanding current position due to inductor positioning	Detects intersections Navigates intersections	Detects intersections with inductors on a 45 degree angle Navigates intersection by measuring voltage on opposite inductors Able to understand position and correct errors
U-Turn	Accurate	Accurate	Accurate
Stop	Accurate	Accurate	Accurate
Remark	Easiest to implement into software.	More hardware than 2 inductors.	More accurate tracking when implemented in software due to more inductors tracking positioning of robot on track. Uses the most hardware.
Design Decision: We chose to use **4 Inductors** because it would track the most accurately and although it uses the most hardware, tracking backwards would be easier because it would be the dual of tracking forwards.			

Table 3.2: PWM Methods for Right Motor

PWM Function [%]	$\lambda_L = 100 \times \frac{V_L}{V_L + V_R}$	$\lambda_L = 100 \times \frac{V_L^2}{(V_L + V_R)^2}$	$\lambda_L = 75 \times \frac{V_L^2}{V_L^2 + V_R^2}$
Description	Simple ratio based on value of opposite inductor and sum of both inductors	Squared ratio	Ratio of Squares multiplied by a lower constant
Forward	Accurate	Inaccurate	Accurate

Tracking			
Details	Smooth movement but unable to make sharp turns. Steers off course at sharp turns.	Slightly more exaggerated difference between motors than option 1, but is problematic for certain voltage values	Movement is less smooth, but can handle all sharp turns. Multiplying it by a lower constant helped with smoothness.
Design Decision: We chose to use the 3rd ratio because it is the most versatile and exaggerates the difference between the left motor and the right motor. Although the movement isn't as smooth, we decided functionality is more important.			

Detailed Design

Before starting on any circuits, we had to decide upon a microcontroller to use for our Guide Wire Generator and Robot Controller. We quickly decided upon the C8051F38C (F38x)[7] for the Robot Controller due to our level of familiarity with it and its overall power to cost ratio.

We then decided upon the ATMega328P[8] for the Guide Wire Generator. The reasons associated with the choice are outlined as follows:

- It met the criteria for a different style of microcontroller as outlined in the requirements (8051/AVR)
- It did not need to be soldered to a perf board
- It did not need to be put into bootloader mode every time it needed to be flashed
- It is a popular microprocessor and has plenty of documentation and support online
- It had a clock speed that, while slower than other available chips, was more than sufficient for our needs

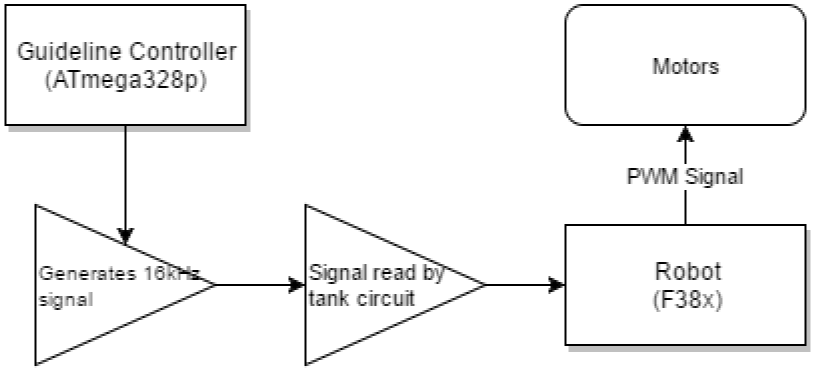


Figure 3.2: Block diagram of full system

Guide Wire Generator

Overview

The purpose of this controller is to provide a square wave signal at resonance frequency in the guide wire the robot is tracking.

ATMega328P is flashed in the identical fashion as the AT89LP52 from project 1. It is connected to a computer via BO230XS such as in figure 3.3. One exception is that ATMEga328P only needs the ‘reset’ button as the microcontroller does not need to be put into bootloader mode manually (mentioned above). This enables much more efficient development flow.

The software for the guide wire generator is split into multiple C files and the files are compiled using *avr-gcc* and *make* in *CrossIDE*.

Signal Generation

ATMega328P has 3 timers/counters: two synchronous timer (Timer 0 and Timer 1) and one asynchronous timer (Timer2). Timer 0 is configured to raise an interrupt at 32kHz. By simply toggling the digital pin 9 (pin D9 in figure 3.4) on every Timer 0 interrupt, a 16kHz square wave is generated in the guide wire.

Timer 0 interrupts has the highest priority out of all other timers. This ensures that a consistent 16kHz is transmitted regardless of other functions in the program onboard.

Guide Wire Communication

We are prohibited to communicate with the guide wire tracking robot via wired communication such as direct control, SPI, etc. We are also prohibited from using RF (wireless) communication such as bluetooth, WiFi, infrared, etc. Thus, in order to send commands to the robot, the only option is through the guide wire. When proper input is given by the user, commands are sent through the guide wire every 1 second.

To start sending commands, which are comprised of bits, the 16kHz is first turned off for 64.0ms. This counts as a ‘0’ bit and tells the track robot to start receiving bits. Then the 16kHz is turned back on for 64.0ms to synchronize timing on the track robot, allowing the following bits to be read consistently.

The next three bits are the “real” data bits that contains the command code. Since we are sending 6 commands, 3 bits (maximum 8 different commands) are deemed appropriate. The 16kHz signal will be turned on or off depending on if the bit that is currently being sent is 0 or 1. Their transfer rates are all also 64ms per bit.

User IO

User determines the commands being sent to the robot using buttons and a joystick. The joystick is basically an assembly of two potentiometers and they are connected to Analog 0 (A0) and Analog 1 (A1) pins on the ATMega328. The x-axis and y-axis analog signal is read by the onboard ADC. Two buttons are connected to two digital input pins for two more commands.

An LCD is attached to the guide wire generator to display the current command being sent. If no command is given, the LCD will display “Awaiting commands”. The attached LED also strobes the individual bits when the microcontroller is transmitting a command.

Magnetic Field Tracking Robot

Tank Circuit

We used 1 uF capacitors in our LC (tank) circuits because they were inexpensive and readily available. To ensure that the signal picked up by the inductors would be the same as the generated signal, we used the formula for resonance frequency as shown below to calculate a guide wire frequency of ~16 kHz.

$$f = \frac{1}{2\pi\sqrt{LC}}$$

To increase the resolution of the data we received, we amplified the output voltage from each tank circuit by a factor of $\alpha = 34$ using the formula, $\alpha = 1 + \frac{R_2}{R_1}$. To capture only the needed peak voltage data points we built a peak detector to create a DC signal of peak voltage that was then read by the microcontroller. Below is the final diagram (figure 3.5) for the combined Tank, Op Amp and Peak Detector circuit.

Receiving Commands

Hardware

In order to receive commands quickly and consistently, we chose to use a digital input rather than an analog input (ADC reading). The software algorithm set two requirements for the hardware: the receiver must receive commands at 15.625Hz (64.0ms per bit) , and the input voltage must meet the requirements for a digital reading (0V signaling logic 0 and 5V signaling logic 1). Based on these two requirements, we designed our receiver using a combination of two comparators and one rectifier[9] circuit. The diagram for the receiver is shown below in figure 3.6.

The first comparator has two functions. First, it transforms a sine wave to a steady square wave. Second, and more importantly, it separates the current from other circuits (e.g. peak detector).

We first tested our receiver circuit without utilizing this comparator and found that the rectifier drains current from other parts of the circuits. It was noted that this had a large negative effect on ADC readings from the peak detector. The rectifier transforms the AC square wave to a DC signal. The AC square wave at 16kHz must be smoothed out by a capacitor to a steady DC signal. At the same time, the capacitor must also discharge fast enough to differentiate the “on” and “off” DC signals from turning on and off the AC square wave at 15.625 Hz. We tested different capacitors to determine the best fit for this requirement and concluded that using 4.7µF capacitor was the best fit. Command transmissions from the guide wire controller were also slowed down from 100Hz to 15.625Hz.

Since the maximum voltage coming out from the rectifier while transmitting is 2.2V, which is far less than the 5 V necessary to indicate logic 1, we decided to use another comparator to boost the maximum voltage while maintaining the same frequency. This allowed us to meet the software requirements without compromising any other parts of the circuit.

Software

Our initial design for receiving commands uses UART. However, we found that determining the baud rate for transmitting data is difficult since UART acts as a blackbox to us. Implementing UART required several issues to be addressed, including noise. This plan requires ample research effort so for the sake of time, we decided to choose the method described below.

Each incoming command from the guide wire begins with a logic 0 detected by an input from the comparator. This triggers the robot to actively read the binary sequence that follows. Commands are read through sampling. Each binary bit is sent for a period of exactly 64.0ms, and the most accurate way to read the bit is at the midpoint of 32.0ms.

There is a logic 0 bit followed by a logic 1 bit which acts as a accurately timed trigger before each command. To offset the delay of polling for logic 0, the robot will wait for a logic 1 once the function has been triggered. This essentially synchronizes the robot with the guide wire controller.

The robot then commences receiving the incoming bit sequence with the correct timing. This method allowed us to easily adjust the code to match the baud rate of transmitted data unlike UART.

Example - Receiving Command: The robot will be triggered by a logic 0, followed by a logic 1 to synchronize timing. Next, the function will wait for 96.0ms (1.5 times 64.0ms) to be at the center of the next bit, and 64.0ms to be at the center of each following bit. The function reads 4 consecutive bits, stores them into a single 8-bit variable, and compares it against the database of commands. Finally, the command is returned if it matched with a known command, or the previous command is returned if an invalid command.

Robot Controller

States	***Description***
1	Tracking forward
2	Tracking backward
3	Stopped

Command	***Received Signal***	***Bits***	***Description***
0		11_**111**	No command
1		01_**001**	Turn left at the next intersection
2		01_**010**	Turn right at the next intersection
3		01_**011**	Switch to tracking forward
4		01_**100**	Switch to tracking in reverse
5		01_**101**	U-Turn (turn 180)
6		01_**110**	Stop

For our robot controller we classified every function of the robot as either a state or a command as described in the table below. Commands take higher priority than states. In execution the robot will check if there are any incoming commands from the guide wire generator and then enter the function associated with its current state. The robot then executes the current command, resets the command to 0, and loops back to the function associated with its current state. In the case of left and right turns, the robot cannot execute the functions immediately so the command is kept and executed if an intersection is sensed. The command is returned to 0 if the turn has occurred or the command can be overwritten by another sent command.

In each loop, the robot checks for sonar readings. If an object is picked up by the sonar to be less than 7 cm away, the robot will execute the stop function as a safety measure and wait until the object has been removed to resume its previous state.

Also in each loop, the current command of the robot or the state stopped is displayed onto an LED matrix. In the case of left and right turns, signal LED lights are set to blink.

While the command is 0 the robot is also searching for intersections. The combined high voltages of the inductors signal an intersection and trigger a function that ensures the robot continues straight through the intersection.

Adjusting Motors:

To control the speed of the motors, we used Pulse-width modulation (PWM) operated by an H-bridge. As a result of changing the duty cycle of the square wave outputted to the H-Bridge circuits, the speed of the motors change. The ratio used for PWM is $\lambda_L = 75 \times \frac{V_L^2}{V_L^2+V_R^2}$.

When a left turn or right turn command is sent while moving forwards, it does not execute until an intersection has been detected. Once the code has been activated by an intersection, the robot first moves straight forwards for 300 ms until it is directly on top of the intersection. Then, one motor is set to 50 PWM forwards while the other is set to 0, allowing the robot to pivot in place. The robot turns for 200 ms in order to move the rear inductors off the current track, and continues to turn until the rear detectors sense the new track. From here, the robot continues on with its current state.

Turns while moving backwards are similar; they are executed only once an intersection has been detected. The difference is that the robot will move backwards to be directly on top of the intersection and the PWM is set in the opposite direction. The command is still dependent on the rear inductors to sense the new track. The rear inductors were chosen to sense the end of a turn because they are farther from the wheels, thus farther from the intersection and reading more accurate voltage values.

When crossing intersections with no current command, the robot should continue forwards. As the intersection interferes with line tracking, it is difficult to predict at which angle the robot will enter the intersection. For example, the robot might sense the intersection while at a 45 degree angle to the line it’s currently tracking and steer off track. In order to prevent this, we assess which rear inductor is higher and turn the robot slightly as it moves through the intersection to adjust. If the right rear inductor has a higher voltage than the left rear inductor, we know the robot is entering the intersection pointing slightly to the right. We then can easily adjust for this by setting the left PWM to 25 and the right PWM to 50 so the robot can resume line tracking properly once it has exited the intersection.

Finally, our function to rotate the robot by 180 degrees sets PWM values to be equal in magnitude but opposite in direction which allows the robot to spin in one spot. The robot spins for 1 second, long enough so the sensors are no longer on the track, and then continues to spin until the sensors sense that the robot is once again on track. At this point, the robot will continue with the same movements as before the interruption of a 180 command.

Solution Assessment

Our team conducted different types of testing to ensure that our design could meet requirements efficiently. Once our final design was built for both the guide wire generator and our robot we recorded testing data. Data was generated by testing commands sent through the guide wire generator while our robot's power was supplied by batteries.

We tested for quality of our robot with our Turn Test (see Appendix), where we scored our robot's turns between 1-10. Scoring below a 5 indicated a failure (i.e did not make the turn), and above 5 indicated a pass. For example, a score of 6 meant our robot made the turn but drove off track and readjusted itself, while a 10 meant the robot executed a perfect turn.

We tested the consistency of our robot with a Consistency Test (see Appendix). This test was pass or fail, depending on whether the robot's execution of a command was successful.

A strength of our design was consistency. When our robot was at its prime voltage level (around 8V), the rate of successful execution was 100% (out of 5 trials).

A weakness of our design was accuracy of turns at different levels of voltage. When the voltage levels were too high (i.e after replacing the battery in our robot), the robot would overshoot turns due to the motors drawing in more current. Similarly, low voltage levels would get our robot stuck during turns due to the motors being too weak to carry the robot's wheels across[1] the wire.

4. Lifelong Learning

One team member learned how to test for broken MOSFETs through online resources. The steps he used are as followed:

- ➔ Use a multimeter set in diode mode
- ➔ Connect the gate and drain of the MOSFET to the multimeter
- ➔ If a voltage can be read by the multimeter; then a current is running through it and therefore the diode inside must be broken

Additionally, ELEC 211: Engineering Electromagnetics was critical for this project; it helped our team better understand magnetic fields, and the course inspired our design decision to place our inductors at 45 degree angles.

5. Conclusions

The foundation of our wire-guided robot was an light aluminum chassis, built to house a breadboard, two motors, inductors, and batteries. Our design features four inductors, two at the front of the robot and two at the back, placed strategically at 45 degrees to the guide wire on the bottom of the chassis to detect intersections, track the wire and navigate intersections both forwards and backwards.

[1] The test is done under non-controlled varying battery voltage ranging from 7.4V to 9.5V

The first breadboard includes circuits to find the amplified peak voltage of each front inductor, H-Bridge circuits for motor control, an F38x microcontroller, and a data transmission comparator circuit.

An additional smaller breadboard is mounted above the first to include peak detector circuits for the rear inductors. Information from all detection circuitry is sent to the F38x where tracking algorithms are used to control the motors' direction and power.

One final breadboard which is isolated from the main setup includes an ATmega328 microcontroller to send commands through the wire to the robot, and a joystick controller for user command input.

Six different commands can be sent to the robot to execute through the main tracking wire. The robot then recognizes each different command by its binary signature and either stores the command or executes it immediately.

Bonus features include sonar to detect objects on the wire path, an LED matrix which displays the current command the robot is executing, brake lights, running lights, and signal lights for turn commands. The robot is controlled using a knob controller in combination with a push button to execute all 6 commands.

There were various problems encountered and overcome in this project. The major problem was intersection navigation, while minor problems included reliability of peak detection circuitry, and the inductors shorting by touching the aluminum chassis and inducing voltages on each other. The amount of time spent on this project averaged 60-70 hours per person.

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Appendix