MAKER: Autonomous Solar-Powered Vehicle as a Learning Tool in Robotics and Green Energy

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Abstract

This paper presents the design, construction, and programming of an autonomous solar-powered ground vehicle by combining advanced autonomous robotics with green energy technology. The vehicle has been based on a customized remote control car whose steering is controlled autonomously using an Arduino microcontroller. The vehicle is able to drive to preset destinations using a global positioning system (GPS) receiver module and a compass to navigate to waypoints until the destination is reached. The vehicle can be powered using a lithium polymer (LiPo) battery that is recharged using solar panels. A maximum power point tracking (MPPT) solar charger is used between the panels and the battery in order to provide the maximum charging current to the battery. A Bluetooth module is used to allow for wireless communication between the vehicle and an Android Smartphone. The paper aims to convey the importance of integrating educational robotics integrated with green energy as a technological learning tool for undergraduate students and explain how it helps students prepare for the future of industry.

Introduction

This paper discusses an educational effort that incorporates green design concept for an autonomous solar-powered car in a senior design project at Drexel University. This senior design project engages students in the implementation of a 3-D printing method for improving design and measuring energy efficiency using solidworks design. This project entails designing, building, and testing an autonomous ground vehicle that can be programmed to navigate autonomously. Green energy technology will also be incorporated into this project through the use of solar energy to provide power for the vehicle. Autonomous vehicles have a number of positive environmental benefits such as reduced fuel consumption that results from reducing the amount of congestion on the roads.

Autonomous vehicle technology is closely related to connected vehicle technology, which enables vehicles to share information with other vehicles on the road. Combining green energy technology with autonomous vehicle technology can further reduce the environmental impact of vehicles. More energy from sunlight strikes the Earth in one hour (4.3 x 10^20 Joules) than all the energy consumed on the planet in a year (4.1 x 10^20 Joules). Therefore radiant sunlight is a clean and abundant source of energy. Solar cells convert radiant sunlight into electricity based on the photovoltaic effect.

This project aims to design, build, and test an autonomous solar powered ground vehicle. The vehicle is autonomous through the use of a global positioning system (GPS). Solar panels can charge a primary battery that powers the DC motor. A maximum peak power tracking (MPPT) solar charge controller is used to extract the maximum amount of energy from the solar panels as well as convert the energy to proper system voltage. The team has created a system that utilizes the Arduino microcontroller as the center of the whole system. It is equipped with a GPS shield that is used to locate the vehicle's position and navigate towards a destination by controlling its steering and acceleration. The Arduino is also be able receive new destinations using Bluetooth. This project aims to design and build a prototype model for an autonomous vehicle that would be designed to help those that would need it the most.

Design of the Vehicle and Autonomous System

The first step in converting the remote control car into an autonomous vehicle was to remove any unneeded components that were not essential to the design. The motors used for steering and driving were originally controlled by a circuit board, which can be seen in the middle in Figure 1. This entire control circuit board was removed and replaced with the Arduino Uno microcontroller and the accompanying GPS shield and motor shield. The shields are special purpose boards that can be plugged on top of the Arduino in order to extend its capabilities. The Arduino used the motor shield to control the vehicle's motor and a GPS shield to receive latitude and longitude coordinates from the GPS module.

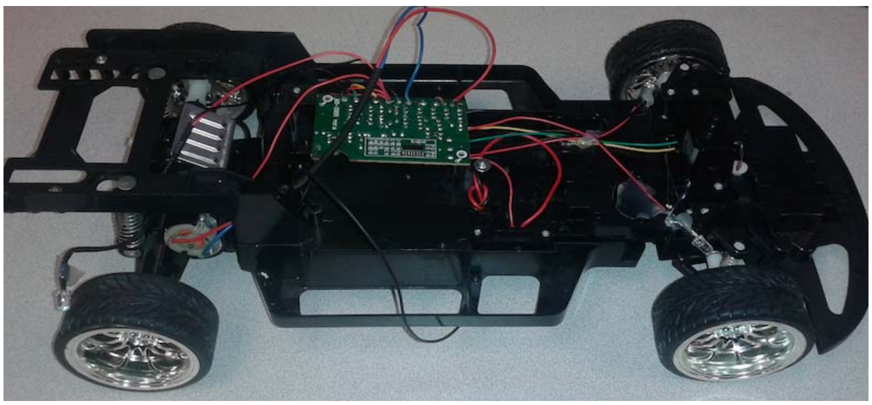

Figure 1: Un-customized Remote Control Vehicle

The Arduino Uno was the microcontroller of choice due to its simplistic programming language, functionality, and cheap price. The Arduino Uno microcontroller is based on the ATmega328. The Uno microcontroller is programmed using the Arduino IDE (Integrated Development Environment) software and the code is downloaded using a USB connection. The Arduino IDE uses a simplified programming language based on C++, which makes it easier to program. The Uno can be powered via USB connection or with an external power supply ranging from 7 to 12 volts. The board contains 14 digital pins that can be used as either an input or output, 6 of which that can be used as PWM outputs, and 6 analog input pins[1].

The GPS module used was the EM-506 GPS receiver. The GPS module requires a clear view of the sky in order to receive signals from satellites and output its time and position as NMEA data. It must be connected to at least six satellites in order to accurately calculate its time and position. The GPS module's serial port is connected to the microcontroller via the GPS shield and sends the NMEA data from the shield's TX pin to the microcontroller's RX pin. In general, the GPS receiver module is connected to the stackable GPS shield. The microcontroller then parses the NMEA data into readable variables such as: latitude, longitude, date, time, altitude, and number of satellites the GPS is locked onto. Figure 2 shows a printout of this data that can be viewed on a computer via the Arduino IDE serial monitor when the microcontroller is connected using a USB cable.

Figure 2: GPS printout

The GPS module will not provide accurate heading updates while the vehicle is turning, so a compass must be used for steering instead of the GPS. The compass is used to determine which way the vehicle is facing so that it can calculate the vehicle's heading (the vehicle's heading is its direction of travel measured relative to magnetic North). The HMC5883L 3-axis magnetometer was used as a digital compass to sense direction. The HMC5883L senses direction by measuring the magnetic field of the Earth. The direction of Earth's magnetic fields affects the flow of electrons in the sensor, and those changes in current are measured and calculated to derive a compass heading relative to magnetic North.

The HMC5883L compass printout is shown in Figure 3. The 'Raw' X, Y, and Z measurements are the magnetic field measurements in units of milliGauss from the compass. The 'Scaled' X,Y, and Z values are the measurements with compensation for the magnetic declination of the location. The magnetic declination angle is the angle on the horizontal plane between magnetic north (direction of the Earth's magnetic field lines) and true north (direction towards geographic north pole). Determining the correct magnetic declination angle is required in order for the compass to produce accurate heading calculations. The team used the website http://www.magnetic-declination.com/ in order to determine the correct value. For Philadelphia, PA the magnetic declination angle is -12° 9' (approximately 0.0457 radians). The arcTangent function was then used to determine the heading angle between the X and Y directions. The heading is printed out in both radians and degrees.

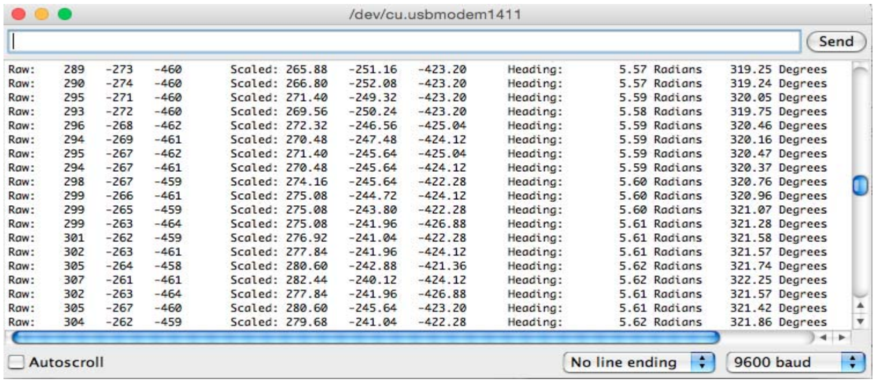

Figure 3: HMC5883L printout

A TowerPro mini servo motor was used to steer the vehicle. The servo can change its angle anywhere between 0 - 180° and steers the vehicle based on the heading measurement from the compass. A custom part, seen below in Figure 4, had to be designed in order to install the servo and connect it to the vehicle's steering arm. The servo bracket was designed using SolidWorks and was then printed out using a 3D printer.

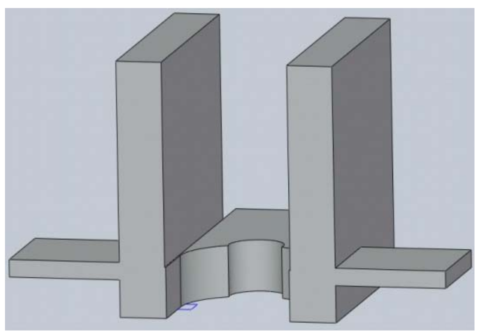

Figure 4: Servo bracket 3D design in SolidWorks

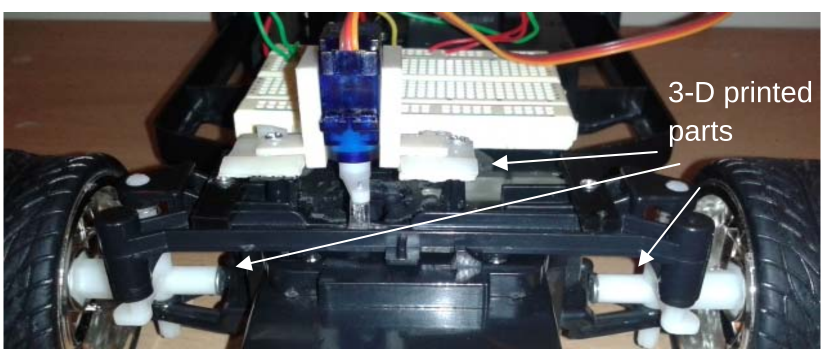

Figure 5: Installed servo bracket and servo

The installed servo and bracket can be seen in Figure 5. The motor was controlled using the SparkFun Ardumoto motor driver shield. This motor shield is based on the L298 two-channel motor driver. A motor driver is required because motors draw more current than the Arduino is capable of handling and the shield allows the Arduino to control a lot of current using a low signal. This motor driver can individually drive up to two motors, but only one is needed for the design. The motor is connected via a screw terminal that was soldered to the shield at port A. Vin on the shield powers both the Arduino and the motor, so the input voltage must fall within the range of the Arduino and meet the requirements of the motor[2-3].

The BlueSMiRF Silver was the Bluetooth module used the prototype design. This Bluetooth module contains a transceiver, which means it can both send and receive data. This Bluetooth module was used to allow for short-range, wireless communication with the vehicle prototype using an Android smartphone. Due to Arduino UNO only having one serial port, the Bluetooth module could only be used when the GPS module was turned off. A separate program had to be downloaded via USB cable to the microcontroller before the smartphone could connect to the Bluetooth module. A third-party app called Arduino RC was installed on the smartphone that allowed for manual control of the vehicle[4-6].

<u>Arduino Program</u>

The program was written using the accompanying Arduino IDE (Integrated Development Environment) software. A basic Arduino program, or ‘sketch’ can be seen below in Figure 6 and consists of two main parts: the setup() function and the loop() function. The setup() function is called once when the program starts and is used to initialize all the variables, pin modes and libraries. The loop() function is used to actively control the microcontroller and loops consecutively.

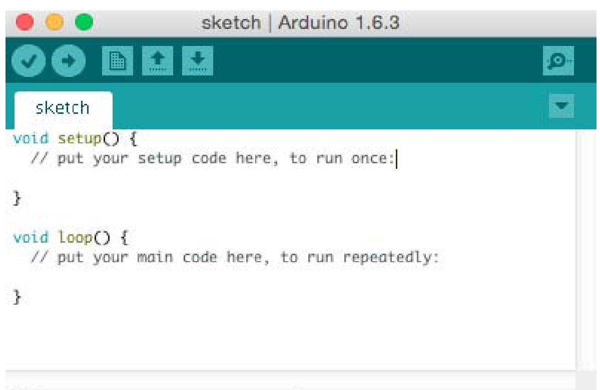

Figure 6: Arduino IDE basic programming structure

The program to operate the vehicle autonomously was designed based off the flowchart in Figure 7. The destination, where the vehicle is to autonomously navigate to, must be manually entered into the program and uploaded to the microcontroller prior to turning on the vehicle. After turning on the vehicle, the GPS module begins trying to connect to satellites. Once the GPS module is connected to at least six satellites, the microcontroller parses the incoming NMEA data into latitude and longitude coordinates. The latitude and longitude coordinates for both the vehicle and the destination are then converted to radians. Next, the distance and bearing to the vehicle’s destination are calculated using data from the GPS. The distance from the vehicle's current position to the destination is calculated using the haversine formula to calculate the shortest distance between two points. After the distance, bearing, and heading variables have been calculated, the program uses control, comparison, and boolean operators to control the vehicle's motor and steering servo autonomously[7-10].

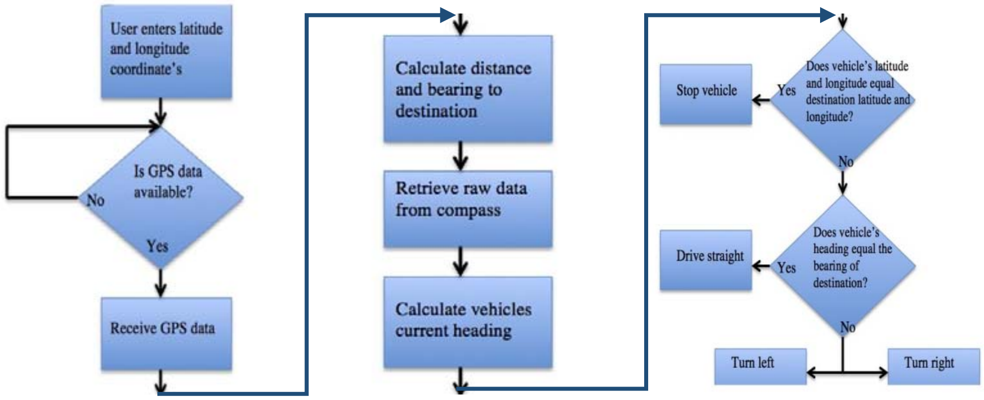

Figure 7: Autonomous program flowchart

Design of Solar System

The solar system consists of the solar panels, the converter, and the rechargeable battery. Two 2.5 W SparkFun brand solar panels (Figure 8) were used in order to provide power to charge the battery. Each solar panel was 7" x 4.5" and is rated for 8 V open circuit voltage and 310 mA short circuit. The open circuit voltage is the maximum voltage available from the solar panel, which occurs at zero current. The short circuit current is the current through the solar cell when the voltage across the cell is zero. It is the maximum current obtainable from a solar cell. These solar panels were chosen for the design based on their sufficient power output and relatively small size. These panels also came shipped with a male barrel plug terminal already attached for easy connectivity[11].

Figure 8: Solar panel 2.5 W with quarter for scale

Solar panels are composed of several cells and therefore are capable of producing a wide range of voltages. A DC-to-DC converter is required in between the solar panels and the rechargeable battery in order to step up or step down the voltage produced by the panels. The Sunny Buddy, which is a maximum power point tracking (MPPT) solar charger, was the converter chosen due to its easy connectivity and maximum power point tracking capabilities. The solar panels and battery were able to be plugged directly into the Sunny Buddy via center-positive barrel jacks and a JST terminal, respectively. This maximum power point tracking solar charge converter is different from other solar charge converters because it varies its voltage in order to operate at the maximum power point. This is because the voltage of a solar panel (and each solar cell making up the panel) varies with temperature and the amount of radiant sunlight hitting it. Therefore, using a maximum power point tracking converter results in a higher maximum electrical power output from the panel[12-16].

The rechargeable battery that was chosen for the vehicle was a 2000 mAh lithium polymer ion (LiPo) battery. This battery contains a built-in safety circuit board that protects against over voltage, over current, and minimum voltage. The battery capacity was chosen based on the power requirements listed in Table 1. The maximum vehicle run time based on these power requirements were calculated as follows: (Battery capacity/Total power consumption) = (2000 mAh/1616.1 mA) = 1.23 hours * 60 minutes/hour = 74.25 minute run time.

Based on these power requirements, the vehicle can operate continuously for more than one hour, which seems adequate for the purposes of this prototype. This calculated maximum run time may vary depending on how hard the motor has to run in order to drive the vehicle. The vehicle's motor demands the greatest amount of power from the battery and factors such as the roughness of the driving terrain or wind may cause the motor to draw greater power and decrease the maximum run time[16-19].

Part	**Power Consumption**	**Operating Voltage**
Arduino Uno microcontroller	46 mA	6 - 20 V
Ardumoto	n/a	n/a
GPS module	70 mA	4.5 - 6.5 V
Servo	n/a	5 V
Motor	1.5 A	5 V
HMC5883L Compass	0.1 mA	2.5 V
Total	**1616.1 mA**	

Table 1: Prototype Power Requirements

Experimental Results

The completed vehicle prototype is shown in Figure 9. The different components of the prototype were connected as shown in the hook-up diagram in Figure 10.

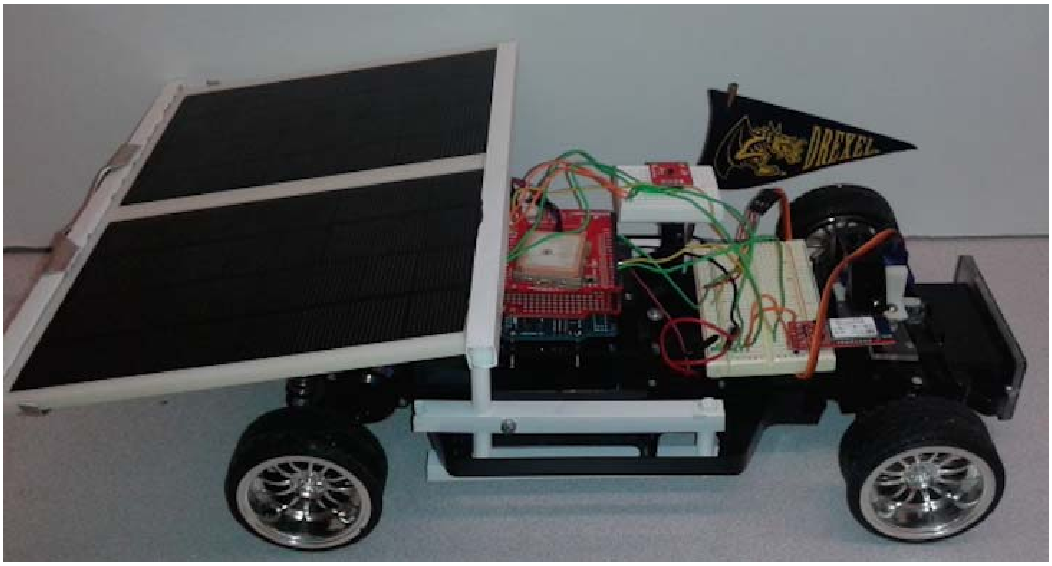

Figure 9: Completed vehicle prototype

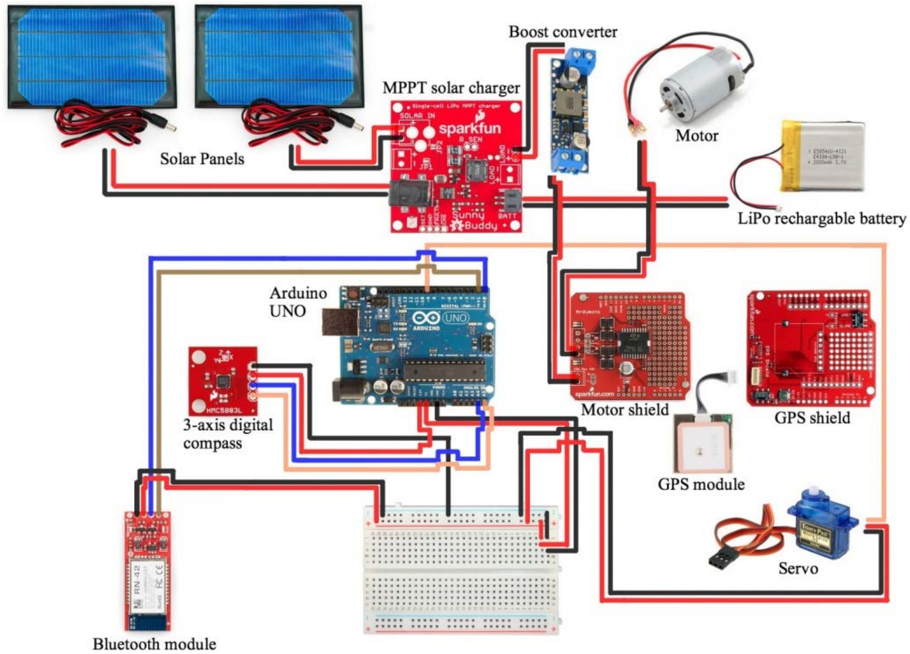

Figure 10: Vehicle hook-up diagram

Autonomous System Performance

The vehicle prototype was able to successfully navigate to programmed locations. When testing the vehicle, the motor would not start running until the GPS module had successfully locked on to a number of satellites, which was indicated by a blinking LED light on the module. Once the GPS was connected, the motor would turn on and the servo would begin steering the vehicle in the direction of the destination's bearing. The prototype would drive straight once the vehicle's heading matched the destination's bearing and the motor would stop when the vehicle's coordinates were equal to the destination's coordinates.

The main limitation of the autonomous system was the choice of microcontroller. The Arduino UNO is cheap and functional, but it is limited in that it only has one serial port. One set of RX and TX pins meant that the UNO could only communicate with one serial device at a time. This prototype's design incorporated two serial devices: the GPS module and the Bluetooth module. Therefore the Bluetooth module was used a manual override that allowed the vehicle to be controlled using an Android smartphone that was paired with the module. This manual override mode required a separate program that had to be downloaded to the microcontroller before the smartphone could be connected to the Bluetooth. The UNO could be swapped for the Arduino Mega microcontroller, which contains four serial ports. This would allow for communication with multiple serial devices instead of just one.

The accuracy of the EM-506 GPS module was another limitation of the autonomous system due to its inaccuracy. The GPS module used in the autonomous design was only accurate to 10 meters, which affected the performance of the prototype. As a result, the prototype had to be tested between points that were greater than 10 meters apart. For example, Table 2 and Figure 11 below show the spread of the GPS module's position data when it was tested standing still at the coordinates (39.955417, -75.189308). After each reset, the module would provide different position data even though it stayed in one spot. The GPS module also became slightly less accurate while the vehicle was moving. Since the GPS module is such an important part of the autonomous system, investing extra money in a more accurate module would greatly improve the prototype's performance.

Latitude	Longitude	Distance From True Position
39.955359	-75.189364	8 meters
39.955392	-75.189286	3 meters
39.955304	-75.189292	12 meters
39.955421	-75.189206	8 meters
39.955268	-75.189364	17 meters

Table 2: Variation in GPS latitude and longitude data coordinates obtained by standing still in one location

Figure 11: Spread of GPS position

Solar System Performance

The solar panels were able to successfully provide power to charge the prototype's battery, but the rate that the vehicle drained power from the battery exceeded the rate that its power was replenished. The minimum charge time for the LiPo battery, based on the measured performance of the solar panels, was calculated as follows:

(battery capacity / max. charge current) = (2000 mAh / 250 mA) = 8 hours to full charge

The battery charge time is the fastest when the vehicle is not operating due to the fact that the prototype consumes power at a faster rate than the solar panels are able to recharge it. An improvement to the prototype's solar system could be to increase the size of the solar panels. A larger solar panel would be able to harness a greater amount of radiant sunlight and a larger charge current would decrease the total charge time.

Despite solar energy's potential as a clean and unlimited energy source, it still provides formidable basic research challenges that prevent it from becoming economically competitive with fossil fuels. The low efficiency with which solar panels convert sunlight to stored energy means that many panels are typically required to produce sufficient energy. Solar energy is diffuse and intermittent and effective storage is critical to matching supply with demand.

Economic Analysis

This project was designated a budget of $500 to design and build a 1/10 scale autonomous solar powered vehicle prototype. The total cost of the materials used in the design of the vehicle was $373.23. The more expensive components of the vehicle were the two solar panels, the GPS module, and the remoter control car. With the cost of labor and for us to make a profit from this prototype final product cost was the retail price for the prototype to be at $933.08. If this product were to be ordered in bulk for 100 units the estimated cost would be $806.23.

Future Improvement

Improvements to the prototype's design could be made by incorporating sensors onto the vehicle to allow it to sense the outside world. Although, this would require upgrading from the UNO to the Arduino Mega board, which contains more than one serial port. Incorporating sensors would enable a collision detection system and allow the vehicle to sense when an object is in its way and navigate around it. Additionally, a more accurate GPS module would allow the prototype to navigate closer distances with greater a precision. The solar system could also be improved by increasing the rate at which the battery is recharged. This could be done by increasing the size of the solar panels used in the design, but this would also require sizing up the scale of the vehicle in order to handle the greater weight from larger panels. Other renewable energies such as fuel cells could also be investigated and incorporated into the prototype's design.

Conclusions

The project begins by defining a performance problem associated with applications and ends with a prototype for a green design solution. The problem drives the learning required to complete the project. Managing the project requires the students to demonstrate effective teamwork, clear communication and the ability to balance the social, economic and environmental impacts of the project. It is believed that problem-based learning, as exemplified by a capstone senior design project such as this one, provides students with important knowledge about green design. In addition, such projects provide students with the essential project management and engineering skills required to bring complex projects from idea to completion. The prototype was successfully able to navigate autonomously to a programmed destination and charge its battery using solar energy. Its performance was dependent mainly on the accuracy of the GPS module. The prototype demonstrated how a manually controlled vehicle, such as a remote control toy car, could be converted into a very basic autonomous vehicle that can drive itself to a specified location. An improved and more advanced autonomous prototype would require a more accurate GPS module, sensors for collision detection, and a more powerful microcontroller.

Acknowledgement

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