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DEPARTMENT OF MECHANICAL AND NUCLEAR ENGINEERING

THE DEVELOPMENT OF A PARALLEL HYBRID RC HOBBY CAR

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Abstract

According to the U.S. Energy Information Administration, transportation accounts for 28 percent of energy used in the United States. Hybrid vehicles can be up to twice as efficient as traditional gasoline vehicles, with only minimal compromise. Electric vehicles are even more efficient and more economical, and offer the potential of personal transportation with near-zero environmental impact. Despite the advantages of hybrid and electric vehicles, surveys indicate that public knowledge about both vehicles is very low. The goal of this project is to develop a parallel hybrid RC hobby car that will eventually aid in educating children and future generations about hybrid and electric vehicles. Our team selected Losi Ten-T as the base car for the conversion. First, I analyzed the mechanical and electrical systems of the car to determine how the car's systems function. Then, our team selected properly sized electric car components, and I converted the car to an all-electric drivetrain. I next developed a parallel hybrid using both the combustion engine and the electric motor. I made some progress in employing a microcontroller to control the engine and motor in the hybrid and to incorporate regenerative braking in the car. The all electric car operated successfully, and the parallel operated successfully using either the motor or the engine. Future plans for the parallel hybrid car include operating the motor and engine in tandem, and employing regenerative braking using the microcontroller.

Contents

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1 Statement of Objective

The goal of the work described in this thesis is to develop a parallel hybrid RC (radio controlled) hobby car, powered by both liquid nitromethane fuel (emulating gasoline) and an electric lithium-ion battery pack. This work is part of a larger effort that includes several projects aimed at improving the public's knowledge of hybrid and electric vehicles. The project related to this work is to develop a children's educational toy car kit that can be easily assembled into a gasoline, electric, or a hybrid RC car. The development of a parallel hybrid RC car provides proof of concept, and acts as a major stepping stone in the development of the children's kit.

The development of the parallel hybrid RC car includes the following goals:

1. Select an appropriate RC hobby car to act as the base for the parallel hybrid car.
2. Analyze the systems of the car to determine how the car functions.
3. Determine an appropriately-sized electric motor and nitro engine for the RC car.
4. Design the component placement in the car, and determine necessary methods for mounting and connecting the components.
5. Incorporate a microcontroller circuit in the car to effectively control the nitro engine and electric motor.
6. Optimize the engine and motor control for fuel economy.

This thesis provides relevant background information on hybrid vehicles and current hybrid educational resources available, and describes the completion of tasks 1 through 4 above.

2 Motivation

In recent decades in the United States, demand for larger and safer cars has led to increases in car weight, and thus lower fuel economy. Hybridization has been an effective method, not only to maintain the fuel economy previously available in the 80s and 90s, but to achieve even higher gas mileage. Most notably, hybrid vehicles archive significantly higher gas mileage in rural driving, which provides substantial benefits to city commuters. For city driving, hybrid vehicles are approximately twice as efficient as traditional gasoline vehicles [2].

In 1999, the Honda Insight became the first hybrid vehicle available to the mass market in the United States [1]. Since then, the number of hybrid vehicles available has increased exponentially (see Figure 1). In the last five years, hybrid vehicles have accounted for 2 to 3 percent of all vehicles sold [3]. A small number of mass market electric vehicle are now available in the United States, with several more being developed by major auto makers.

However, even with the increase in popularity of hybrid and electric vehicles, a significant percentage of the public appears to be largely uninformed about hybrid and electric vehicles. In a 2010 survey of almost 2000 intended buyers of new vehicles, only half of the respondents indicated that hybrid vehicles contain batteries, and only 64 percent indicated that hybrid vehicles use both a combustion engine and an electric motor [4]. The complete results of the survey are presented in Table 1.

Because transportation is the second largest area of consumer spending (higher than food and healthcare) [5], Americans must be able to make well-informed decisions regarding their vehicles. The educational toy

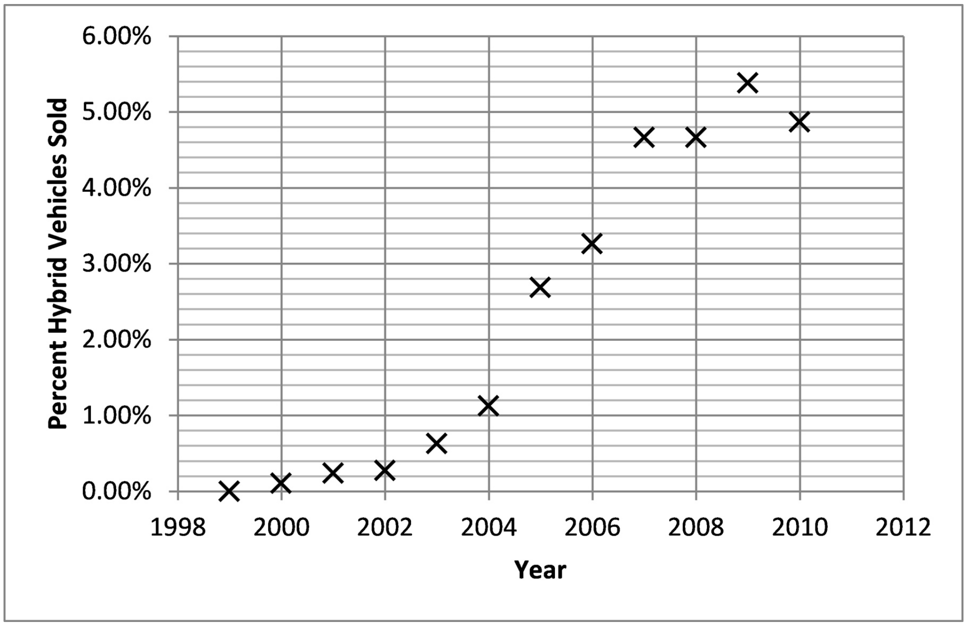


Figure 1: Growth of U.S. hybrid vehicle development in recent years [3].

Table 1: Percent of responders who believe the statement applies to the vehicle type [4].

Statement	Electric	Plug-in Hybrid	Hybrid
Contains electric batteries	77	59	50
Has zero tailpipe emissions	66	40	28
Needs to be plugged in to charge the batteries	67	65	28
Needs a special cord that goes from the vehicle to the electrical socket	56	69	29
Takes more than 15 minutes to re-fuel	49	51	28
Should be plugged into a 220 volt charging outlet	58	62	26
Can run on the electric motor only	65	42	35
Has a maximum range of around 150 miles	59	44	27
Can use an extension cord of no more than 20 feet in length with the plug	52	64	25
Uses both gasoline to power an internal-combustion engine and batteries to power an electric motor	15	39	64
Uses gasoline as a fuel source	11	33	58
Uses hydrogen as a fuel source	13	16	23

car kit will provide an interactive, hands-on learning experience to children, thus effectively educating future generations about how gasoline, hybrid, and electric vehicles function, and the advantages and disadvantages of each.

3 Background

By definition, hybrid vehicles are cars that utilize two or more fuel sources for propulsion. Nearly all vehicle hybridization has involved combining gasoline engines and electric motors. The engine and motor can be combined in three different structures: parallel, series, and power-split. Some hybrids, known as plug-ins, offer the option of recharging the battery from a wall outlet, though they still utilize one of the three aforementioned structures. All three offer different advantages, but each allows for the following primary benefits of hybridization:

1. Regenerative braking - With the inclusion of an electric motor, during braking the motor can be operated in reverse to act as a generator, recharging the battery. This allows hybrid vehicles to save some of the kinetic energy of the vehicle that would typically be lost during traditional heat-dissipative braking.

2. Optimal engine operation - Most hybrids, either inherently or through the use of a special transmission, allow the engine to operate at its most efficient speed (RPM). This not only reduces gas consumption, but decreases engine wear, too.

3. Engine downsizing - Because the propulsion of the vehicle is shared between two power sources (electric motor and gasoline engine), the engines in hybrid vehicles can typically be significantly smaller than those in gasoline-only vehicles. Smaller engines are inherently more efficient than larger engines.

3.1 Types of Hybrid Vehicles

The addition of a second power source allows for some flexibility in the path of power from the two fuel sources to the car. The following sections describe the different types of hybrid drivetrains, and compare and contrast the advantages and disadvantages of each.

3.1.1 Parallel Hybrid

In the parallel hybrid, the paths of each power source (electric and gasoline) are parallel to each other. Typically this means that the gasoline and electrical systems are separated, but connect at the drive shaft (see Figure 2). However, for conversions, the systems may be completely separate in the car. In this case, the engine may provide power to the front wheels, and the motor may provide power to the rear wheels. This is referred to as a "through-the-ground" hybrid. During regenerative braking in a parallel hybrid, the engine is disengaged from the drive shaft, and the electric motor acts as a generator to recharge the battery.

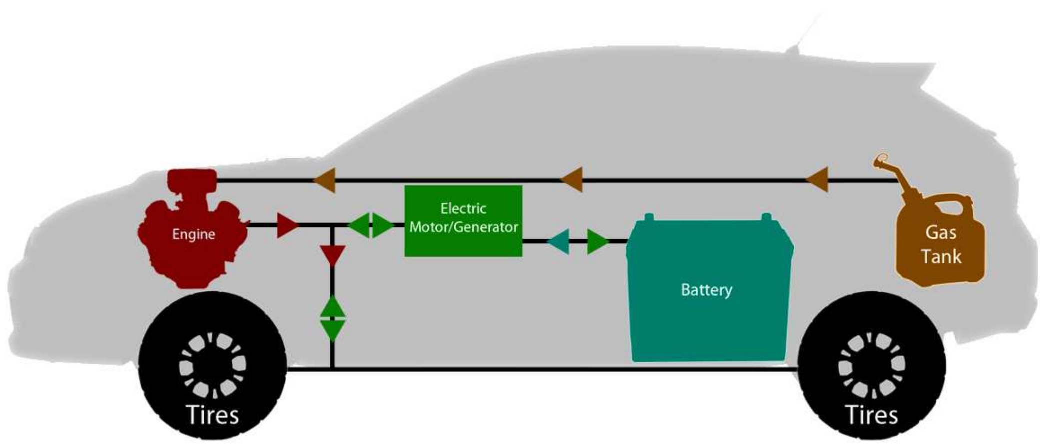


Figure 2: Schematic of a parallel hybrid.

Parallel hybrids can be considered the simplest hybrid configuration in terms of components and controls required. Gasoline cars can be most easily converted to parallel hybrids, especially if they are through-the-road. Parallel configurations also allow for significant engine downsizing. However, parallel hybrids have disadvantages due to their simplicity. In parallel hybrids the engine does not always operate in its optimal speed range. Continuously variable transmissions (CVTs) can be employed to noticeably increase efficiency, but there will still be variation in engine speed and performance. The engine is also unable to provide power directly to the motor in order to recharge the battery.

3.1.2 Series Hybrid

In the series hybrid, the path of the power is in a straight line, from component to component (see Figure 3). First, the engine produces mechanical power from gasoline. That mechanical power is fed into a generator, which charges the battery. The electric motor that drives the car pulls power from the battery. Note that for this configuration, only an electric motor drives the car, though a combustion engine produces the electrical power. Typically, the engine will be in one of two states: off (even while the car is still in transit) or running at a constant, optimal speed to generate electricity.

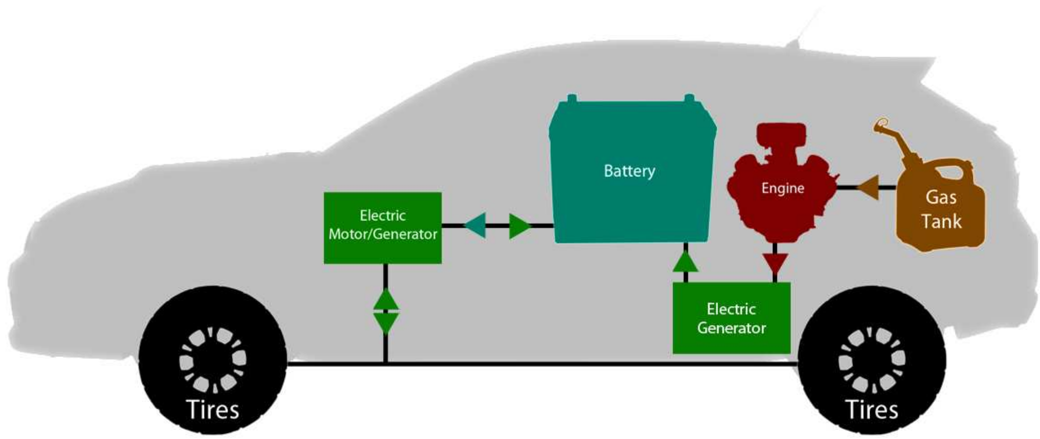


Figure 3: Schematic of a series hybrid.

Series hybrids require an additional generator (motor) compared to parallel hybrids, but have several advantages. First, the engine is always able to operate at its most efficient speed. Additionally, series hybrids are more effective as plug-in hybrids, because they can run off of electricity alone. However, because the car is propelled just by the electric motor, the motor has to be more powerful. Additionally, the engine can only be minimally downsized, because it still has to provide the entire energy required to move the car.

3.1.3 Power-split Hybrid

The power-split hybrid uses a planetary gear box (referred to as a power-split device) to allow the car to function as a parallel, a series, or a mix of the two. This power split device allows for power to be distributed between the wheels, the engine, and the motor in any possible fraction (see Figure 4). For example, the engine can be running at a constant speed, with some power directed to the wheels, and some power directed to the motor to recharge the battery. The car can also be powered by the electric motor alone, but generally only at lower speeds and lower acceleration rates. During regenerative braking, power from the wheels is directed to the motor, and the battery recharges.

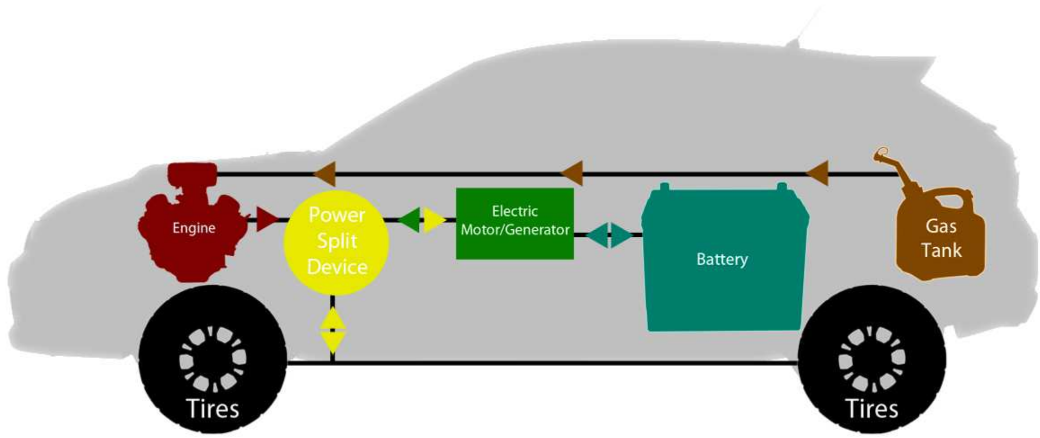


Figure 4: Schematic of a power-split hybrid.

Power-split hybrids have advantages of both parallel and series hybrids. The engine can be downsized significantly, but is also able to run at its most efficient speeds. Additionally, the power from the engine can be directed through the power-split device to recharge the battery. However, power-split hybrids require complex control systems.

3.1.4 Plug-in Hybrid

Plug-in hybrids are simply any hybrid (one of the three previously mentioned types) that can be plugged into an electrical outlet in order to recharge the battery. The advantage to this is that the vehicle can temporarily use more electrical power from the battery and less gasoline. For this to be significantly advantageous, the hybrid should have a larger battery, though plugging-in provides some benefit in any hybrid. In hybrids that have a large enough electric motor to propel the car completely, the hybrid can travel for up to 100 miles (depending on the battery size) using only the outlet-charged battery. These are known as extended-range electric vehicles, because for typical daily driving they can operate without using any gasoline.

3.2 Current Educational Resources

Educational toys work on the principle that the physical assembly of the toy should be easy, but determining how to assemble it in order to achieve a specific goal should be challenging. An example of this is the LEGO Mindstorms NXT kit (Figure 5). The robots are relatively easy to construct and simple to program, but building a robot to perform a certain task is more difficult. Children have to determine how they will both assemble and program the robot in order to have it complete the task. Children learn from considering how previously constructed robots function, thinking ahead to how their robot may work, and trial and error. This environment allowing open-ended development is exciting and rewarding for children, and in turn highly educational.

By their nature, RC hobby cars generate a very similar learning environment to the LEGO Mindstorms NXT kits. Although some RC cars can be bought pre-assembled, many can be bought unassembled, or

Figure 5: Toy robots built from the LEGO Mindstorms NXT kit [Image from mindstorms.lego.com].

individual components can be bought to be assembled. The components are typically standardized throughout the industry, which makes assembly easy. Additionally, some manufacturers make simpler (and less expensive) RC car kits. For example, Elenco makes a simple RC car kit that costs between 20 and 30 dollars [Amazon.com]. The challenge to constructing typical RC hobby cars is in determining which components to buy. The builder has to determine what the car should be able to do, and how to select the right components to meet that goal.

RC car kits are available for electric and combustion-powered cars, as well as hydrogen fuel cell and solar cars. However, no kits are available for hybrid cars, despite the popularity of hybrids. Additionally, the standards for RC hobby cars do not allow for hybrid vehicles to be easily constructed. Despite these obstacles, some people and organizations have constructed hybrid (nitromethane and electric) RC cars. The most notable is the hybrid car constructed by EcoHawks team at the University of Kansas (Figure 6) [6].

The hybrid RC car developed by the EcoHawks is a mix between a parallel hybrid and a power-split hybrid. The RC car uses a planetary gear system to distribute power between the electric motor, the nitro engine, and the wheels of the car. However, the motor is never used as a generator to recharge the battery. Essentially, the two power sources only operate in parallel. A notable shortcoming of this vehicle is that no on-board computer exists to control the engine and the motor. Instead, the driver manually adjusts the throttle of the engine and the motor individually.

4 Design Process

The design of the parallel hybrid RC car was sequential with respect to the complexity of the systems. In other words, I employed simpler systems first, and then added on to or revised existing systems to add complexity. Though this involved some redundant design, it was beneficial for two reasons. First, it provided a valuable learning experience for my partner and me. Second, it allowed for a working product to be available at several stages throughout the design process.

As part of the educational toy car kit project, the design of the parallel hybrid vehicle was concurrent with the design of a series hybrid vehicle. Because some tasks, such as the selection of the base RC car, also depended on the design of the series hybrid, decisions were weighted on factors from both designs.

Figure 6: Hybrid nitro/electric RC car constructed at the University of Kansas [6].

4.1 Selection of Base RC Car

Selecting a complete RC car (or RC car kit) as a starting point, rather than selecting individual components, provides several advantages. First, individually selecting components could result in some required parts being overlooked. Second, the complete RC car contains parts that are known to be compatible. Third, ordering a complete RC car requires much less time than individually selecting components. Fourth, the components in the complete RC car have been sized correctly.

My partner and I used the following criteria (followed by their explanation) to select the base car.

- Has a nitro (gas) drivetrain - Because nitro drivetrains are much more complex than electric drivetrains, determining compatible nitro components to add to an electric car is difficult. Starting with a nitro base car ensures that all necessary nitro parts will be included, sized correctly, and compatible.

- Small enough for one child to carry - This includes dimensions and weight of the car, and is also helpful for transporting the car during design and construction.

- Large enough to work on easily - The components should be large enough so that the car can be easily assembled and disassembled with adult-sized hands. Additionally, large, easily-identifiable components provide a more welcoming learning environment.

- Includes a self-starting engine - One benefit to most hybridization schemes is that during certain driving conditions the engine can be turned off, instead of left idling. Including this feature in our hybrid car would require the use of a self-starting nitro engine, rather than the traditional hand-started engine.

- Is available unassembled - An unassembled kit is preferable, because constructing the car from scratch provides an excellent experience for gaining familiarity with the components and how they function together.
- Has space for additional components - Constructing the hybrid cars will require adding several parts including at least a battery, a motor, and a motor control.

The RC car that best meets these criteria is the Losi Ten-T Truggy, shown in Figure 7. The Ten-T is a four-wheel-drive 1/10 scale nitro RC car. It is 17.75 inches long and weighs 6.2 lbs, which meets the criteria regarding size. The extended front and rear axles provide additional space where components can be placed, while still remaining between the tires. The Ten-T is also one of the few RC cars that includes a self-starting engine. However, it is only available as a fully assembled car.

Figure 7: The Losi Ten-T Truggy with the body cover removed.

The selection of unassembled RC cars was very limited, and finding unassembled nitro cars that met most of the criteria was very difficult. Because of this, the Ten-T was the best choice. To become familiar with the car's components, I disassembled the car to a point where I was able to determine the purpose of each component. The car remained unassembled until I added the electric drivetrain components. (Note that nitro engines require a break-in period, so I ran the car through multiple tanks of fuel before disassembling it.)

4.2 Systems Analysis

RC hobby cars have several discrete components, with mechanical or electrical connections that are frequently standardized. For the analysis I divide the car into six major systems:

- Electrical
- Steering
- Engine
- Starter
- Drivetrain
- Brakes

Table 2 lists the major components required for any given drivetrain, and Table 3 lists the major components unique to the nitro drivetrain.

4.2.1 Electrical Analysis

The electrical systems of the car are used to transmit signals and power. The radio receiver is the central hub of the system. It receives signals from the radio controller and redirects them to the other components, and it receives signals from sensors and redirects them to the radio controller. Note that the battery connects directly to the starter controller, so electrical power routes through both the starter controller and the radio receiver.

I used an oscilloscope, a multimeter, and a microcontroller to determine the signals that the car's components use to communicate. Table 4 lists the electrical power and electrical signals (and their respective wires) that the components use. The microcontroller can reproduce the steering servo, starter controller, and throttle servo signals, and can read the RPM sensor and temperature sensor using the Basic code provided in Appendix A.

The RPM sensor uses a photosensor to detect a metallic target attached to the rear drive shaft. The RPM sensor sends a pulse each time the target is detected, which is once per drive shaft revolution. The combination of pulses effectively acts as a PWM signal, which can be read to determine engine RPM or car speed (if the gear ratio of the rear differential and the rollout are known). Note that the RPM correlation provided in Table 4 is for the drive shaft RPM.

The temperature sensor is a simple thermocouple. The resistance of the thermocouple is dependent on the temperature of the junction. The radio receiver measures the resistance through the thermocouple and sends that information to the radio controller, which determines temperature from the resistance. The correlation is provided in Table 4.

Table 2: Purposes of the major components required for all RC cars.

Component	Purpose	System
Radio Receiver	Handles (sends and receives) all signals, including those to and from the radio controller, those from sensors, and those to servos and other components. Receives power from the battery through the starter controller, and distributes this power to the steering servo, throttle servo, and sensors.	Electrical
Steering Servo	Receives electrical power and a PWM signal from the radio receiver and assigns a rotational position to its pinion, thus angling the front wheels of the car	Steering/Electrical
Lithium-ion Battery	Provides power to the steering servo, throttle servo, radio receiver, and starter controller (including glow plug and starter motor). Must be charged manually at an electrical outlet.	Electrical
RPM Sensor	Receives electrical power from the radio receiver. Emits a pulse each time the rear drive shaft rotates. Uses a small reflective sticker to "count" rotations.	Electrical
Temperature Sensor	A thermocouple that changes electrical resistance as temperature changes. The change in resistance is measured by the radio receiver.	Electrical
Differential	One differential at the center distributes power between the front and rear wheels. Two additional differentials (one in front, one in rear) distribute power between the left and right wheels.	Drivetrain

4.2.2 Steering Analysis

The steering system consists of a high-torque servo that rotates an arm to turn the front wheels. The steering signal from the radio controller is sent to the radio receiver. The radio receiver then sends a PWM signal to the steering servo, which the servo converts into a rotational position of the steering arm. The trim is adjusted digitally within the radio controller.

4.2.3 Engine Analysis

The purpose of the engine system is to convert nitromethane fuel into mechanical power. This involves storing nitromethane, delivering nitromethane to the engine, delivering air (for combustion) to the engine, and removing the exhaust gases from the engine. The starting system for the engine and the system to transfer the mechanical power from the engine to the wheels are considered separate systems for this analysis.

The fuel tank stores the nitromethane fuel. The fuel line connects the fuel tank to the carburetor, and another line (the pressure line) connects the fuel tank to the exhaust system. Air pressure from the exhaust systems pushes fuel out of the fuel tank and into the carburetor. The fuel line inside of the fuel tank has a weight on the end, so that as the vehicle shifts the end of the fuel line moves with the fuel.

The throttle servo receives a PWM signal from the radio receiver, which the servo converts into a rotational position of the throttle arm. This throttle arm controls a pin within the carburetor that controls

Table 3: Purposes of the major components unique to the nitro drivetrain.

Component	Purpose	System
Starter Controller	Receives power directly from the battery and distributes power to the radio receiver. Turns on the starter motor and the glow plug when it receives the "start engine" signal from the radio receiver.	Starter/Electrical
Starter Motor	Receives power from the starter controller and revolves the nitro engine at a constant speed as the engine is being started. Can only engage the engine in one direction.	Starter/Electrical
Nitro Engine	Receives a fuel/air mixture from the carburetor, compresses the mixture above its autoignition temperature, causing combustion, and expels the used fuel/air mixture into the exhaust system. This process generates mechanical power that the engine sends through the crankshaft to the clutch.	Engine
Glow Plug	Powered by the starter controller to electrically heat the cylinder head so that the fuel/air mixture reaches the autoignition temperature during a cold start.	Starter
Exhaust System	Receives the exhaust gases from the nitro engine. Muffles the noise from combustion, and receives a significant portion of the heat generated by combustion. Redirects some of the air pressure from the exhaust gases into the fuel tank.	Engine
Fuel Tank	Holds the nitromethane fuel. Receives air pressure from the exhaust system, which pushes fuel to the carburetor.	Engine
Air Filter	During intake (piston expanding), air is drawn through the air filter and into the carburetor.	Engine
Carburetor	Receives air passing through the air filter and fuel from the fuel tank, and combines the two. During intake (piston expanding) the nitro engine pulls the air/fuel mixture from the carburetor.	Engine
Clutch	Disengages the nitro engine from the drivetrain when the car is still to allow the engine to idle, rather than stall.	Drivetrain
Throttle Servo	Adjusts an actuator in the carburetor to control the amount of fuel that is fed into the nitro engine, effectively changing the fuel/air ratio in the mixture.	Engine/Brakes

the amount of fuel that can enter the carburetor. The carburetor receives fuel from the fuel line and air from the air filter. The pin controlled by the throttle arm effectively adjusts the ratio of fuel to air that is collected in the carburetor. When the piston in the engine expands, the fuel-air mixture in the carburetor is pulled into the engine.

The nitro engine uses a two-stroke cycle for combustion. After the piston motion pulls the fuel-air mixture into the cylinder, the mixture is compressed and heated above its autoignition temperature. Once

Table 4: Electrical signals to and from the components in the car, relative to the radio receiver.

Component	Orange Wire	Red Wire	Brown Wire
Steering servo	Provide PWM: 1.1ms to 1.9ms	Provide +5V DC	neutral
RPM sensor	Receive PWM: $RPM = 29033554PW^{-0.9304}$	Provide +5V DC	neutral
Temperature sensor	Resistance across orange/brown measured: ^{o}F: $T = 121 - \frac{R}{32}$		
Starter controller	Provide PWM at 2.044ms to engage	Receive +5V DC	neutral
Throttle servo	Provide PWM: 1.32ms to 1.84ms	Provide +5V DC	neutral

that occurs, the fuel spontaneously combusts, releasing heat and pressure. The pressure pushes the piston downward and provides mechanical power through the crankshaft. Immediately after the piston begins to recede, the high-pressure gas flows out of the engine into the exhaust system. The exhaust system diverts some of that air pressure from the engine exhaust into the fuel tank to push fuel down the fuel line into the carburetor. As the piston continues to recede, the back pressure of the exhaust gases push more fuel-air mixture into the cylinder. The piston compresses the mixture again, and the process repeats.

4.2.4 Starter Analysis

The starter system, comprised of the starter controller, starter motor, and glow plug, is used to start the nitro engine (from room temperature in most cases). The starter controller receives the signal to start from the radio receiver. The starter controller then provides power to the starter motor, which begins to turn the nitro engine. (Note that the starter motor can only engage the engine in one direction, so during normal operation the engine does not affect the starter.) As the engine turns, it pulls in fuel and air from the carburetor, but this mixture is not able to spontaneously combust at first. This is because the heat generated when the piston compresses the fuel is quickly lost to the cold engine block. The result is that the fuel-air mixture does not reach the autoignition temperature. To remedy this, the starter controller provides power to a glow plug on the cylinder head. The heat provided by the glow plug reduces the heat lost from the fuel mixture, and spontaneous combustion can occur. After only a few revolutions, combustion warms the engine to a point where the glow plug is no longer needed. The user must manually disengage the starter system by releasing the “start” button on the radio controller.

4.2.5 Drivetrain Analysis

The drivetrain system receives the mechanical power from the engine crankshaft and redirects it to the wheels. The clutch operates by utilizing a mechanism that engages only when the engine is running above idling speeds. Inside the clutch bell, two plastic shoes are connected to the crankshaft via a spring. As the crankshaft rotates at faster speeds, the centripetal force causes the shoes to move away from the crankshaft and come in contact with the clutch.

The power from the engine is transferred through several gears and differentials before reaching the wheels. First, a pinion on the clutch bell transfers power to a differential spur gear that connects to the front and rear drive shafts. The differential distributes power between the front and rear drive shaft. Both drive shafts also connect to a differential between two wheels: the front differential between the two front wheels, and the rear differential between the two rear wheels. These three differentials allow for power to be distributed not only left to right, but also front to rear.

4.2.6 Brakes Analysis

Because the nitro engine cannot be run in reverse to brake the car (like an electric motor can), two disc brakes are used: one on the front drive shaft and one on the rear drive shaft. The throttle servo engages the brakes when the throttle arm is rotated in the backward direction (opposite the direction to throttle the engine). This simplification allows for only one servo to be needed for both braking and accelerating, which also reduces the number of signals that the electrical system has to handle.

When the throttle servo rotates to engage the brakes, two calipers squeeze each disc, which are coupled to the drive shafts. This causes the car to slow. Note that by applying the brakes, the throttle servo also reduces the engine to an idle, thus disengaging the clutch. This prevents the brakes from stalling the engine (as can happen in a car with a manual transmission).

4.3 Electric Conversion

I decided to first convert the RC car to a pure electric car, rather than a hybrid, for a few reasons. First, my partner and I had not previously worked with an electric drivetrain, so building a full electric car first, rather than a hybrid, would allow for easier troubleshooting of any issues. Second, the educational toy car kit should be able to be constructed into an electric car, so constructing an electric car serves as a proof of concept, providing evidence that the selected electrical components will allow the car to operate correctly.

4.3.1 Component Sizing and Selection

The car requires three additional components in order to be operated as a full electric: an electric motor, an electronic speed control (ESC), and a battery. Although a battery for the nitro car already exists, a larger battery is necessary for extended runtimes (longer than 5 minutes). The motor should be sized properly to the weight of the vehicle, including the weight of the nitro components when it is a hybrid.

I selected the 21.5 turn Novak Havoc Spec brushless motor for the car (shown in Figure 8). The Havoc Spec is a 540 size motor, which is typically used on 1/10 scale cars. This motor offers several turn counts from 10.5 to 21.5. Typically, fewer turns allow for higher power, but provide less torque; more turns provide more torque, but allow for less power. The reasons for this have to do with the electrical resistance and the strength of the magnetic field in the motor. More turns will generate a stronger magnetic field, thus providing higher torque. However, more turns requires more wire, resulting in a higher resistance. This generates heat faster than a motor with fewer turns, so the power must be limited in order to prevent overheating.

I selected a high torque (high turn count) motor in order to compensate for the extra weight on the car. In this case, high power is not essential for the operation of the car. Typical RC hobby cars have a top speed of over 30 or 40 mph. Not only are cars difficult to control at this speed, but they can be dangerous. For the educational toy car kit the top speed of the vehicle will be limited to no more than 20 mph, so using a less powerful motor is not an issue.

Novak includes an ESC with the Havoc Spec motor (shown in Figure 8), which is what I used for the initial build. This ESC does not allow for regenerative braking (the energy is simply dissipated as heat), but regeneration is a key feature of hybrid vehicles. After contacting several RC companies, I learned that regenerative braking is no longer included in ESCs (from any manufacturer), because the energy saved is very small. For educational purposes, my partner and I decided that later in the project we would build an ESC with regenerative braking.

Figure 8: Components of the electric drivetrain, from left to right: battery, ESC, motor.

I selected a 7.4 Volt, 5300 mAh (milliamp-hour) battery for the car (shown in Figure 8). This battery has a slightly larger capacity than typical batteries on 1/10 scale vehicles, which may be beneficial for the hybrid car, as it has extra weight.

4.3.2 Component Design and Placement

The three components described in Section 4.3.1 all require a mechanism to be held securely in place on the car. This is especially important for the electric motor, because it can generate significant amounts of torque. I decided to build a mounting bracket for the electric motor and to use Velcro to mount the battery and ESC to the car.

For the motor I machined an aluminum mounting bracket (see Figure 9) that connects to the chassis of the car. The bracket for the motor mounts in a similar fashion to the mounting brackets for the nitro engine. Channel holes in the chassis (see Figure 10) allow the motor to slide left to right on the car, but prevent any rotation. This provides two advantages. First, the motor can slide to align the pinion and spur gears so that they mesh correctly. Second, pinion gears of different sizes can be used without any additional machining.

One significant obstacle I encountered is that the size of the center differential makes placing the motor difficult, because there is no clear orientation that allows the pinion to contact the spur gear. As a work-around, for the electric conversion the nitro engine was left in the car. This way the motor pinion could be in contact with the engine pinion, and provide power to the spur gear indirectly as shown in Figure 11. For the educational toy car kit, the electric version should not have the engine on-board. To accomplish this, a chain and sprocket connection could be used, the differential mounts could be modified, or a free gear could be added on a mounting plate in place of the engine.

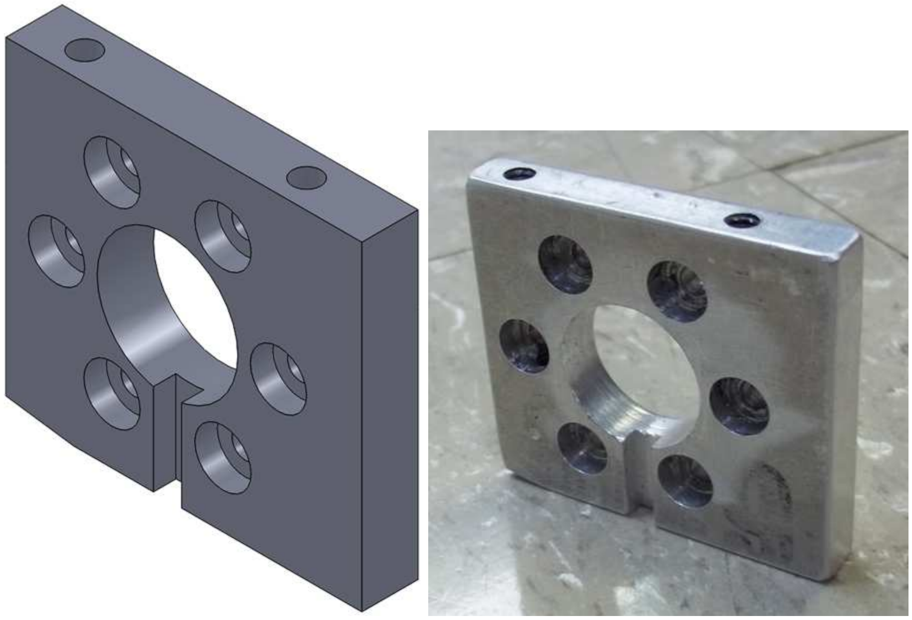


Figure 9: Computer model of the motor bracket (left) and machined motor bracket (right).

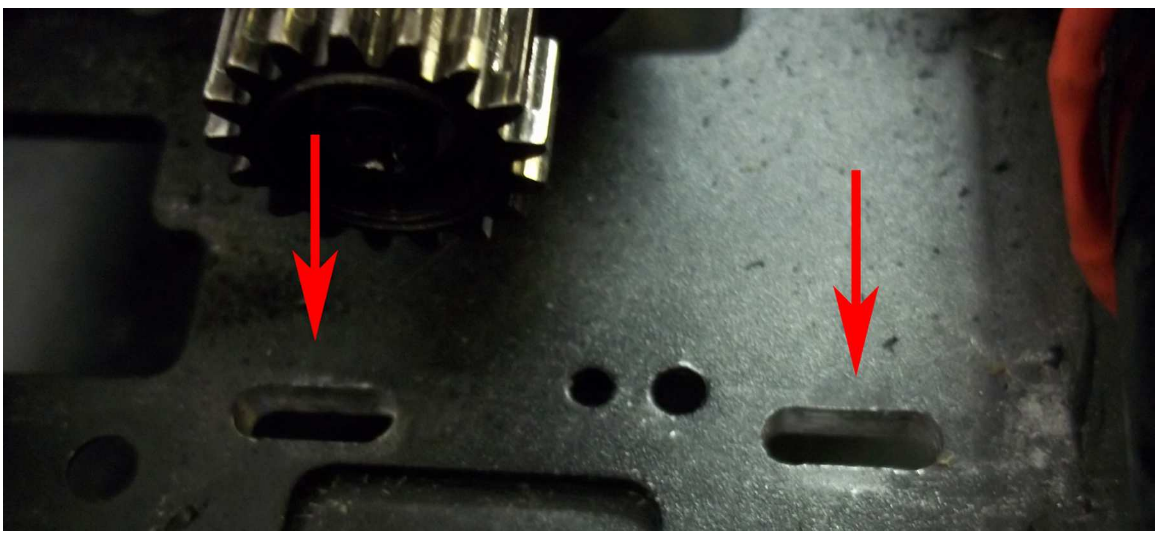


Figure 10: Two channel holes on the car chassis for mounting the electric motor.

After removing the nitro components and mounting the motor in place, the room left by the exhaust system fit the battery and the ESC well. Velcro, both on the side and the bottom of the plastic chassis extension, holds the battery and the ESC in place. Note that during intense runs (high acceleration and deceleration) the motor could heat up significantly and possibly damage the battery.

4.3.3 Assembly and Results

I completely assembled the car using an electric drivetrain as shown in Figure 12. I kept the engine in place in order to provide a connection from motor pinion to spur. The car tested successfully with regard to the following: Using a gear ratio (spur to pinion) of 3.2, the car was able to accelerate equally as well as with

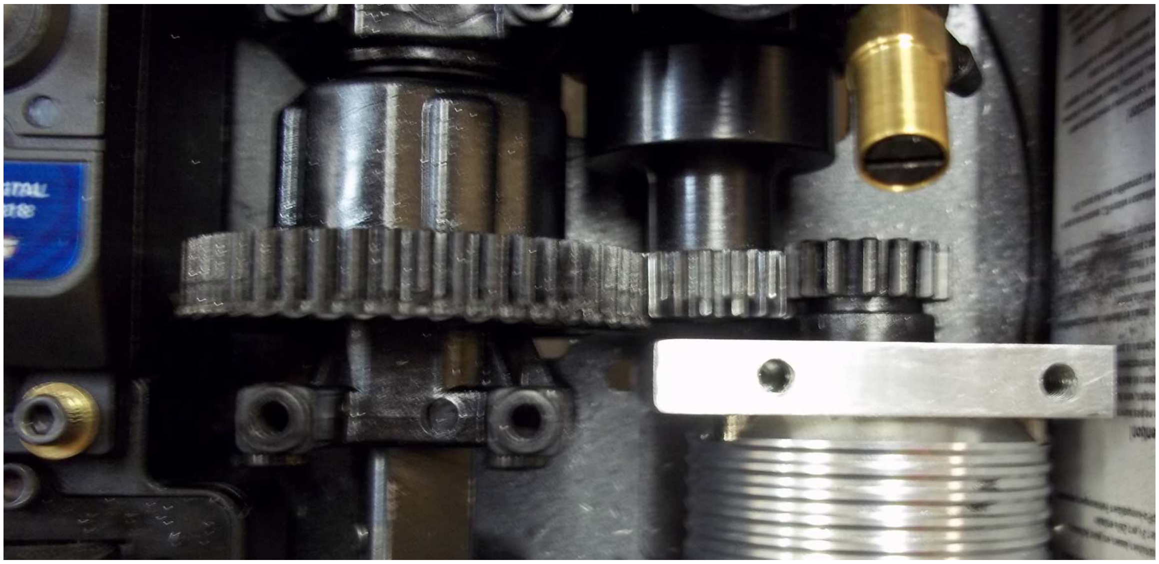


Figure 11: Gear arrangement on parallel hybrid car. Left: spur gear and center differential. Center: engine clutch bell and pinion. Right: motor pinion.

the nitro drivetrain. Additionally, the motor did not exhibit any significant temperature increase above the ambient temperature. Even after intense runs with maximum acceleration, the motor had not noticeably heated up. The car was also able to achieve a top speed of 15 mph, which is significantly slower than the nitro version, but satisfactory for the educational toy car kit.

I also noted two areas for improvement from the test runs. First, the car appeared to not be able to brake. The ESC supports braking (just heat-dissipative braking, not regenerative), but even with it turned on I was not able to get the car to brake well. Second, the pitch of the motor pinion was slightly different than that of the spur and engine pinion. During the testing, this resulted in the gears grinding together. Eventually this resulted in visible points of wear on the teeth of the engine pinion, where the surface was significantly worn down. A more detailed explanation of how I selected appropriate gears for the hybrid version is explained in Section 4.5.

4.4 Parallel Hybrid Conversion

After converting the car to a full electric drivetrain, I next decided to build a parallel hybrid, rather than a series, for several reasons. First, because the ESC does not allow for regenerative braking, building a series requires building a motor control that can effectively regenerate. The parallel is less restrictive because motor regeneration is not necessary in order for the car to work. Second, I had already mounted the motor in parallel with the nitro engine in order for the motor pinion to be able to transfer power to the drivetrain, so building a hybrid would require less modification.

The hybrid does not require any additional components beyond what is already included in the nitro car and the electric car. However, fitting all the parts on the chassis and placing them so that they function properly is much more difficult on a hybrid compared to a full nitro car or a full electric car.

4.4.1 Component Design and Placement

The following considerations regarding component placement can significantly affect vehicle performance:

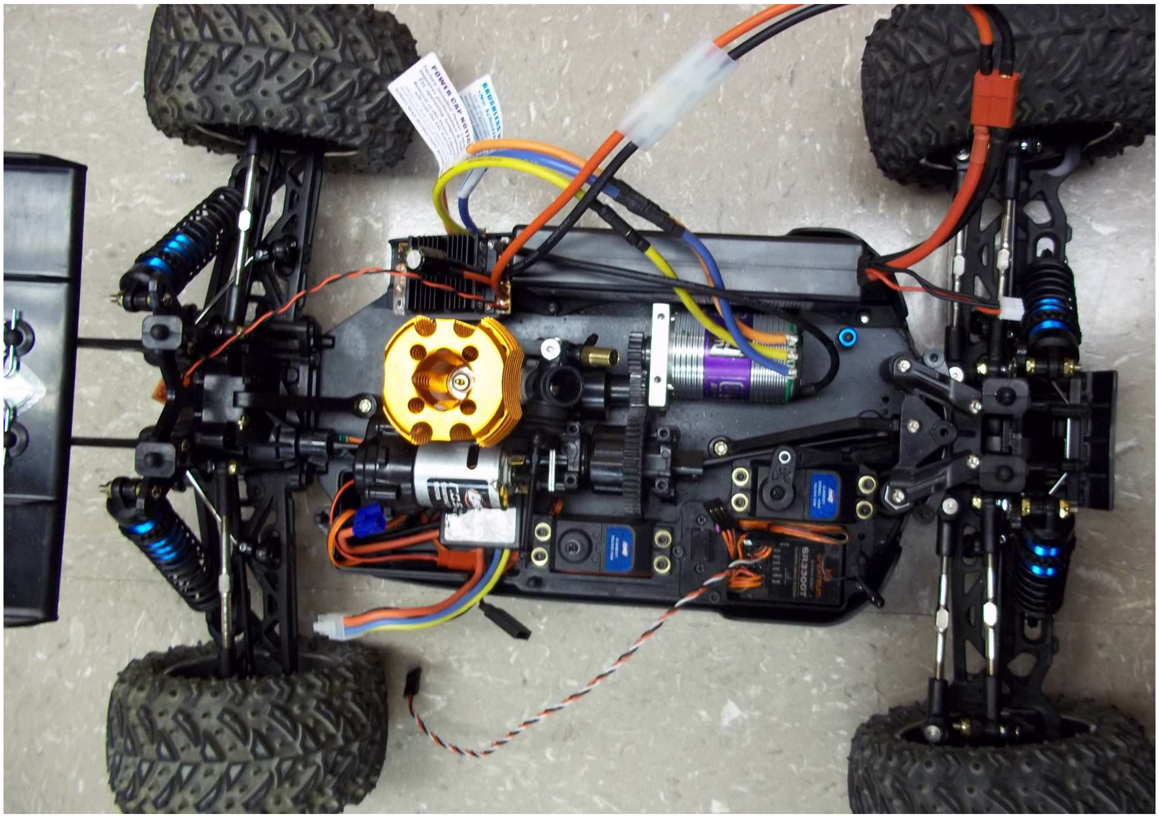


Figure 12: RC car converted to an all-electric drivetrain.

- The car should be balanced left to right, and front to back so that the weight is evenly distributed between the four wheels.
- The center of gravity of the car should be low to the ground to avoid rollovers.
- Components that generate significant amounts of heat should be separate from each other and separate from heat-sensitive components (such as the battery).
- Components should be kept as close to the center of the car as possible to reduce rotational inertia.
- Components should remain between the wheels and above the chassis, so that they receive little or no damage in collisions.

As mentioned in section 4.3.2, for the electric car the motor already was in parallel with the engine, but the engine was left unengaged. For the parallel hybrid, the motor and engine remain in the same place. However, the remaining nitro components must be added to the car. To meet the above requirements, I made the following placement decisions.

I mounted the fuel tank on top of the electric motor, as shown in Figure 13. I designed and created an aluminum plate on which to mount the fuel tank (see Figure 14). Note that the actual component differs from the computer model, but contains the same functional features. Because the fuel tank is on two small plastic stilts, only a small portion of the heat from the electric motor should be transferred to the fuel tank. Although this does raise the center of mass of the car, it is not very significant because the electric motor is smaller than most of the other components. Placing the fuel tank on top of the motor also helps to balance the car left to right, based on where I chose to place the battery.

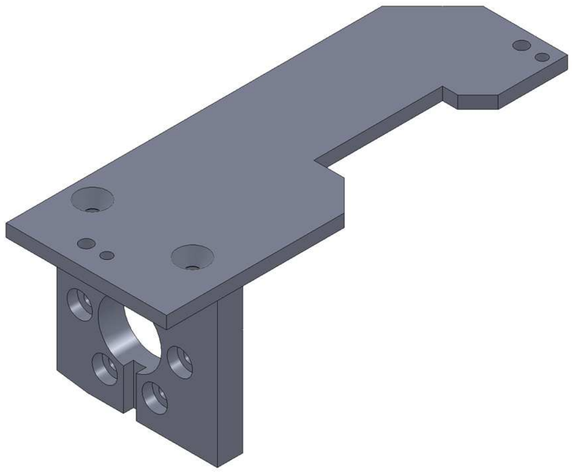



Figure 13: Computer model (left) and actually assembly (right) of fuel tank and motor bracket.

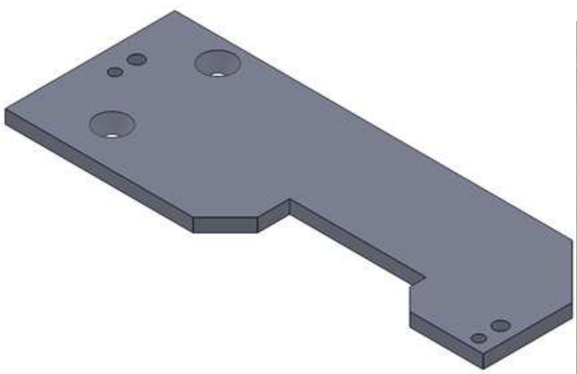



Figure 14: Computer model of fuel tank mounting plate (left), and actual machined part (right).

I created two aluminum clips (see Figure 15) to hold the battery on the right side of the car, and I removed a portion of the plastic chassis extensions so that the battery remains in place. This placement creates the most imbalance in the car, but it should be noted that the majority of the weight is on the left side of the car, though not as far from the center. For example, the nitro engine, the fuel tank, and the motor are all on the left side.

I remounted the exhaust system into its original position on the all-nitro car. I found this to be significantly simpler than the alternative, which would have been to rotate the exhaust system connection at the nitro engine to lift the exhaust system above the chassis. This, however, does not provide enough space for other components to be placed underneath the exhaust system, so there would be little benefit from doing so.

I mounted the air filter in its original location on the all-nitro car, since this did not conflict with any of the other components. This was beneficial because the original mounts were able to hold the air filter in place, and the original tubing from the air filter to the carburetor could be used.

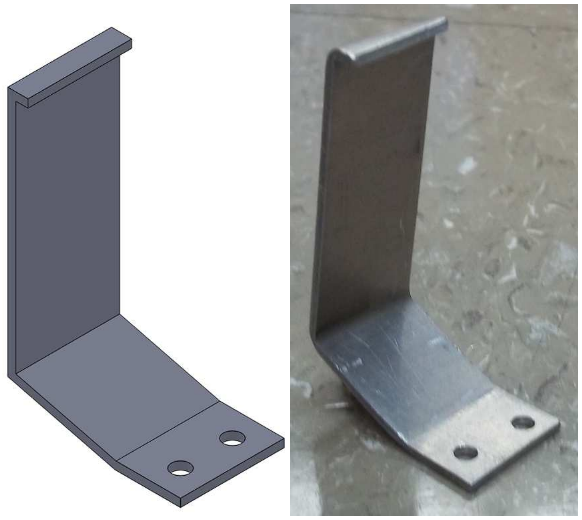


Figure 15: Computer model of the battery mounting clip (left), and the actual machined part (right). Two clips hold the battery in place.

I mounted the ESC above the steering column, using an aluminum plate shown in Figure 16. The ESC was glued to the mounting plate using glue pads that were sold with the motor and ESC. Then, the mounted plate was screwed against the supports that previously held the plastic body cover.

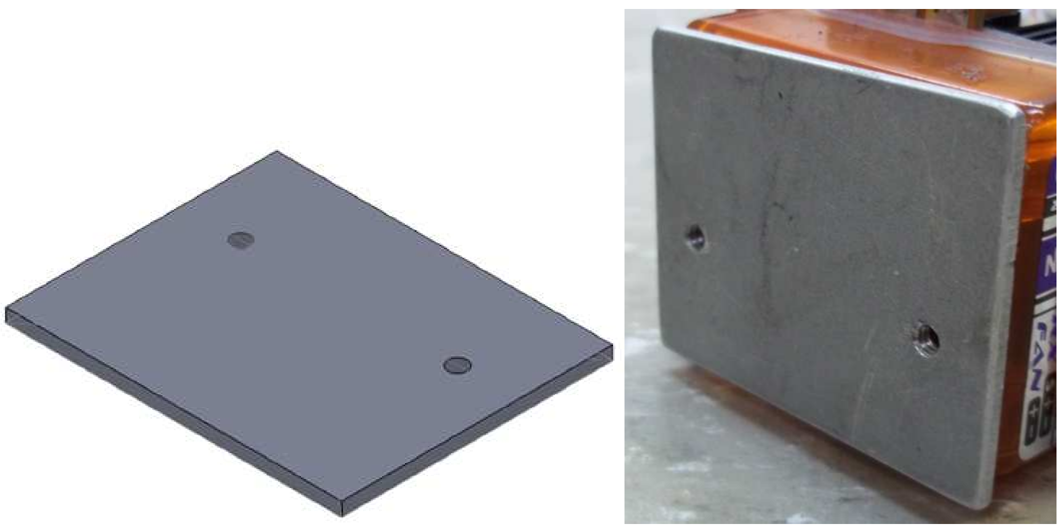


Figure 16: Computer model of ESC mount (left), and actual machined part (right).

4.4.2 Assembly and Results

I completely assembled the parallel hybrid car (shown in Figure 17), and was able to partially operate it. Because I did not have appropriately-meshing gears, I did not operate the vehicle using both power sources. However, I did operate the car using each of the power sources individually. Both performed well during the brief operation despite the extra weight on the car. Using only the electric motor, the car exhibited fast acceleration and was able to reach comparable top speeds to the all-electric car. Due to the gears grinding, I only operated the car in this manner briefly. I also operated the car using just the nitro engine. Again, the car performed well. It accelerated quickly and reached speeds above 30 mph.

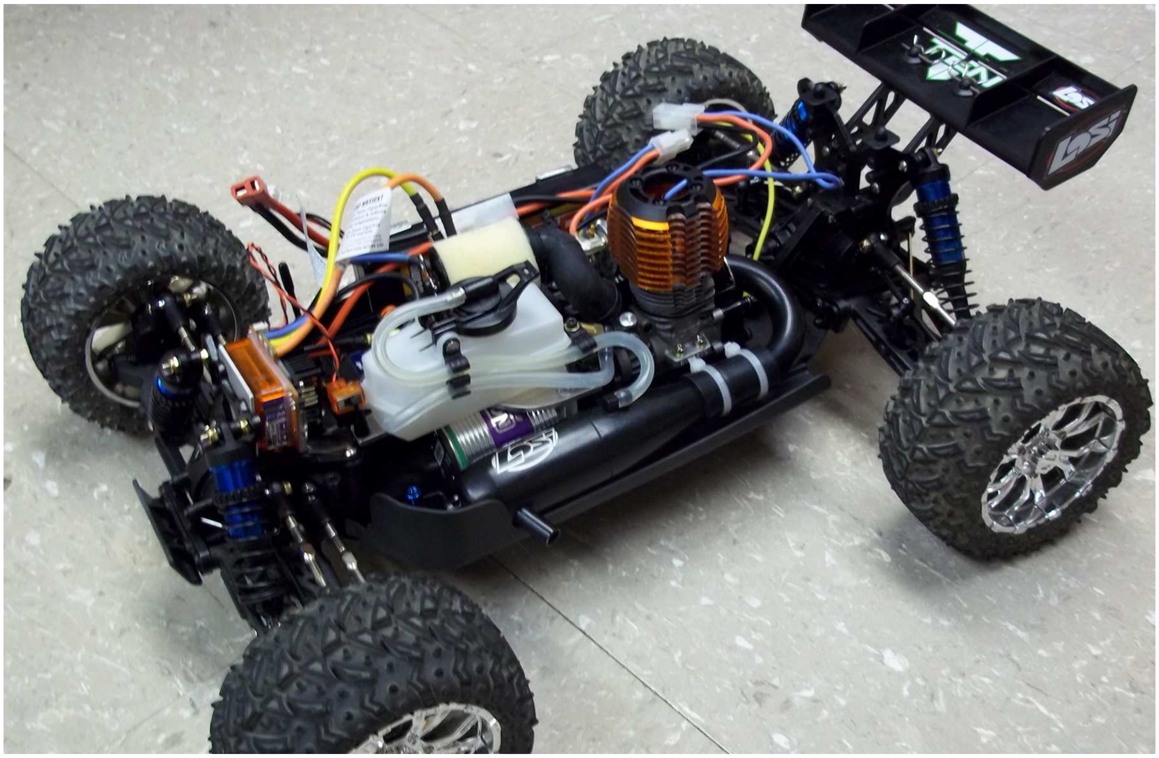


Figure 17: Assembled parallel hybrid car.

4.5 Gear Selection

A significant obstacle to performing both the electric and hybrid conversions was obtaining spur and pinion gears that mesh. This was because I received misinformation about the stock gears on the Ten-T from many resources. The stock gears on the Ten-T have a mod 0.9 pitch, but nearly all the distributors and manufacturers (including Losi) claimed that the Ten-T uses mod 1.0 gears. A few thought that the gears were mod 0.8 (almost exactly the same as 32 pitch). Only one distributor agreed that the gears were neither mod 0.8 nor mod 1.0.

The mod 0.9 gears that Losi uses in the Ten-T are proprietary in the RC car/boat/airplane industry. Mod 0.8 and mod 1.0 gears are readily available in a large variety of sizes. However, I was unable to find mod 0.9 gears. Instead, I decided to change the spur gear and the engine pinion gear to be mod 1.0, which is a common gear pitch used in the both electric and nitro RC cars.

The mod 1.0 spur gear for the Losi Ten-SCTE (part number LOSB3436) is interchangeable with the one from the Ten-T. For the engine pinion, I plan to ream the hole of a mod 1.0 pinion intended for an electric motor so that the pinion can be thermally fit on the clutch bell. This way, all three gears (spur, motor pinion, engine pinion) will be mod 1.0. This will also allow for easier modifications to gear sizes later on.

5 Discussion

This project proved to be successful in producing an electric car and a partial parallel hybrid conversion of a nitro RC car. Additionally, I developed significantly as an engineer throughout the course of the work. In this discussion, I will first consider the success of the product, and then provide reflection on the overall project and experience that I gained.

5.1 Product Critique

I am very satisfied with both the electric and parallel hybrid cars. In both cases I was able to include all the necessary components with minimal alterations to the original car. This reduced the work needed to modify the car, but also provided a more realistic prototype for the educational toy car kit for the following reasons:

- The car was relatively well-balanced left to right and front to back.
- The center of mass of the car remained low to the ground.
- The electric car was smaller than the original nitro car, and the parallel hybrid was only slightly larger than the original nitro car.
- The all-electric car was able to run with acceptable acceleration and top speed (15 mph).
- Using only the electric motor, the parallel hybrid car was able to run with acceptable acceleration and top speed.
- Using only the nitro engine, the parallel hybrid car was able to run with acceptable acceleration and top speed.
- The components were firmly mounted to the car.

5.2 Reflection

This project provided me with excellent opportunities for learning and for self-development as an engineer. In terms of general engineering knowledge, I became familiar with the following:

- Gasoline, electric, and hybrid vehicle systems and efficiency
- Power electronics, including brushless motor control
- Internal combustion engine operation
- Brushed and brushless electric motor operation
- Microprocessor control, specifically with the Basic Stamp
- PWM signals and servo control

As an engineer, I further developed the following skills:

- Approaching new and unfamiliar problems
- Non-destructively analyzing unfamiliar systems

- Designing and producing precise parts
- Designing components to fit together and function as a whole

I am pleased with both the electric prototype and the parallel hybrid prototype, and I enjoyed developing both. However, there are a select number of decisions that, with hindsight, I could have handled better.

- I would have selected an electric motor with specifications similar to those of the nitro engine. Although the motor that I chose is powerful enough for the car, it is significantly less powerful than the engine. For the series hybrid and the eventual power-split hybrid, the motor should be at least as powerful as the nitro engine when operating at its optimal speed.
- I would have tried to mount the battery closer to the center of the car to provide better weight balance left to right.

5.3 Future Plans and Future Work

As mentioned in Section 1, the work that this thesis describes is part of a larger project to develop an educational toy car kit for children. A child should be able to construct the kit into a nitro (representing gasoline) car, electric car, or one of three hybrid cars: parallel, series, or power-split. Regarding the parallel hybrid prototype, I plan on completing the following work:

- Utilizing the microcontroller for regenerative braking
- Utilizing the microcontroller for controlling the electric motor and nitro engine together
- Mounting the microcontroller to the car
- Running the car with power from both the electric motor and nitro engine simultaneously
- Optimizing the power distribution between the electric motor and nitro engine
- Testing the car to determine if it is functioning properly

Future work for the educational toy car kit could include the following:

- Continuing to develop the series and parallel hybrids
- Optimizing all car drivetrains
- Developing a power-split hybrid
- Developing mechanisms to attach and detach components from the chassis without requiring the use of tools
- Developing software for the Basic Stamp to control the different drivetrains
- Developing child-safety features for the kit

References

[1] Taylor, A., 2006, "The Birth of the Prius," *Fortune Magazine*, Vol 153, No 4.

[2] Hermance, D., and Sasaki, S., 1998, "Hybrid electric vehicles take to the streets," *IEEE Spectrum,* Vol 35, pp. 48-52.

[3] 2011, "Hybrid Electric Vehicle (HEV) Sales by Model," *Alternative fuels and Advanced Vehicle Data Center*, U.S. Department of Energy.

[4] Sung, H., 2011, "Synovate survey reveals whether consumers will stay away from electric powertrain vehicles because they don't understand how they work," *Synovate*, Web.

[5] 2011, "Consumer Expenditure Survey," *U.S Bureau of Labor Statistics*, U.S. Department of Labor.

[6] Pro, W., et al., 2010, "1/8 Scale Parallel Hybrid Truck," *The University of Kansas*, Unpublished.

A Glossary

Basic Stamp A microcontroller developed by Parallax. It uses Basic as the programming language.

Brushed Motor A motor that mechanically alternates the flow of electrical current to properly rotate the shaft. Similar to alternating pedaling on a bicycle.

Brushless Motor A motor that electronically alternates the flow of electrical current to properly rotate the shaft. Similar to alternating pedaling on a bicycle.

Clutch Shoes Plastic pieces that are intended to generate significant friction against a specific surface.

Cold Start The process of starting an engine after it has been off for a long enough period of time to cool to near room temperature.

Continuously Variable Transmission (CVT) A type of transmission (similar to a manual or automatic transmission in a car) that can be adjusted to produce any gear ratio from the input to the output.

Drivetrain The group of components in a vehicle that generate power and deliver it to the wheels.

Electronic Speed Control (ESC) A simple computer that controls the operation of an electric motor.

Glow Plug An electric heating device that increases the temperature of the cylinder head in diesel engines so that the fuel combusts spontaneously. The glow plug is used while the engine is started. It is somewhat analogous to spark plugs in gasoline engines, though it only operates during ignition.

ICE Acronym for "internal combustion engine."

Microcontroller Essentially a scaled-down computer, both in size and power, that can be programmed to interface with a large variety of devices, such as sensors, motors, and servos. The microcontroller includes a processor, RAM, flash storage, and several pins used to interface with different devices.

Nitromethane (Nitro) A liquid fuel used in small internal combustion engines on RC cars. Often abbreviated to "nitro."

Planetary Gearbox A gearbox that distributes power and torque between the three connected components.

Pulse Width Modulation (PWM) An electronic signal consisting of pulses. The length of the pulse, typically in microseconds or milliseconds, is varied to act as an analog signal.

Rollout The distance a car travels during one complete rotation of the wheels.

Servo An electric motor designed to have very precise position control. Servos can be controlled by PWM.

Trim The balance in a system between two conditions. In the RC car, the trim refers to the default condition of the steering (left to right balance) and the throttle (acceleration to brake balance).

B Basic Stamp Component Interfacing Code

The following code snippets show how to interface the Basic Stamp 2 (BS2) with individual components in the car. Note that the commands assume that the component is connected to pin 0. That number can be changed to correspond to any pin to which the component may be connected. For most components, one wire connects to the +5 V source, one wire connects to the ground, and one connects to an input/output pin. Refer to the Basic Stamp manual for more information.

B.1 Temperature Sensor

The follow code measures the resistance of the temperature sensor and determines the temperature in degree Fahrenheit. Note that the temperature only has two wires: one should be connected to a pin, one should be connected to the ground.

```
HIGH 0
PAUSE 1
RCTIME 0, 1, resist
tempF = 121 - (resist / 32)
```

B.2 RPM Sensor

The following code recieves the signal from the RPM sensor and determines the RPM of the rear drive shaft. Note that the Basic Stamp does not allow exponents in calculations, so the correlation presented in Table 4 cannot be used. The correlation presented below provides an estimate of the actual correlation. The largest deviations occur at very low (roughly less than 1000) and very high (roughly greater than 15,000) RPM.

```
PULSIN 0, signalIn
pulsewidth = 2*signalIn
RPM = 2814*(10000/signalIn)
```

B.3 Throttle/Steering Servo

The following code sends a PWM control signal to either the throttle servo or the steering servo. The signal ranges are given in Table 4.

```
PULSOUT 0, (0.5*pulsewidth)
```

B.4 Radio Receiver

The following code receives the steering or throttle signal from the radio receiver.

```
PULSIN 0, signalIn
pulsewidth = 2*signalIn
```

B.5 Starter Controller

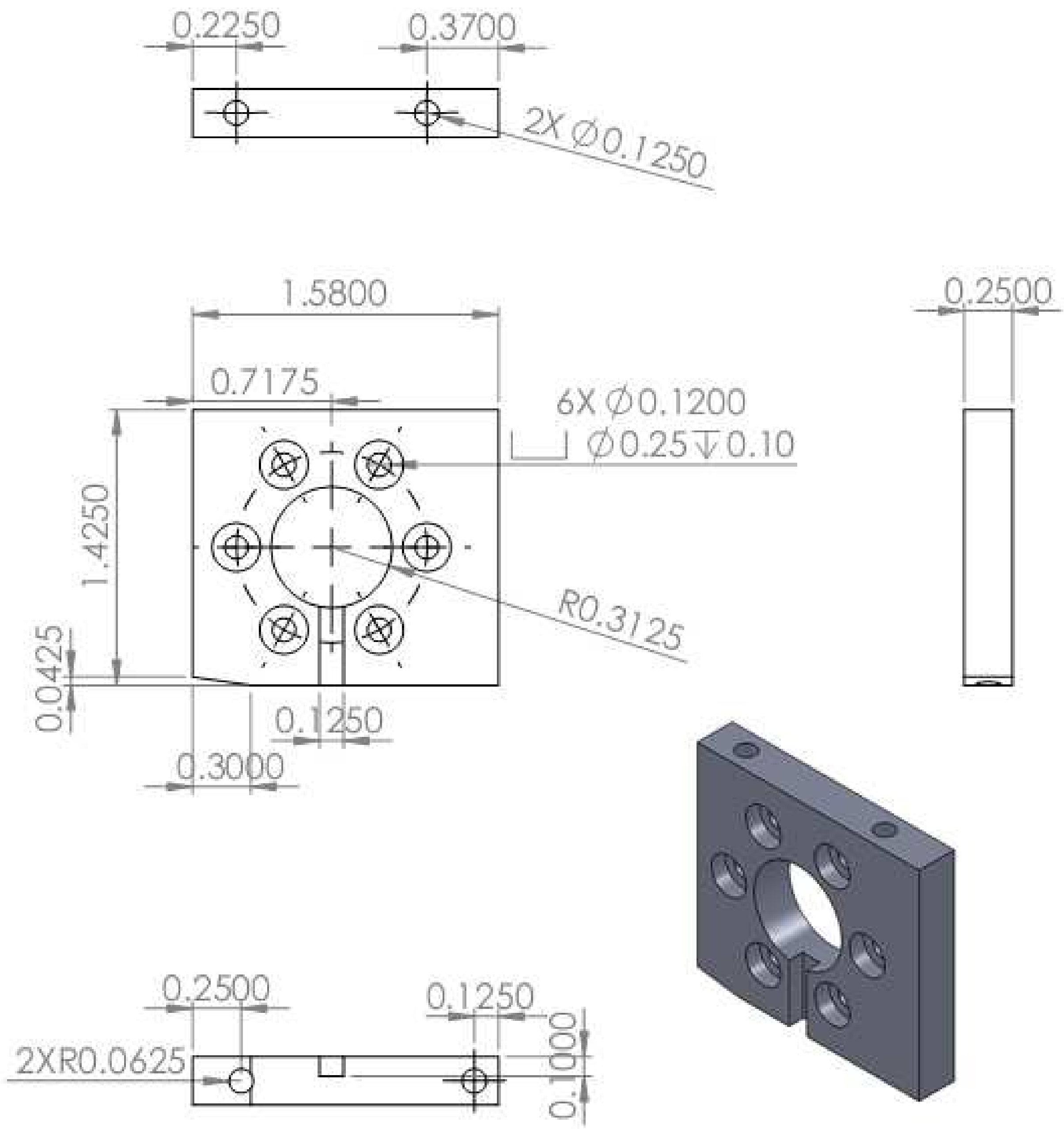
The following code makes the starter controller initiate the starting sequence for the nitro engine. The first line initiates the starter components (starter motor and glow plug). The second line is the default pulse sent when the starter is off.

```
PULSIN 0, 1022
PULSIN 0, 506
```

C Engineering Drawings of Machined Components

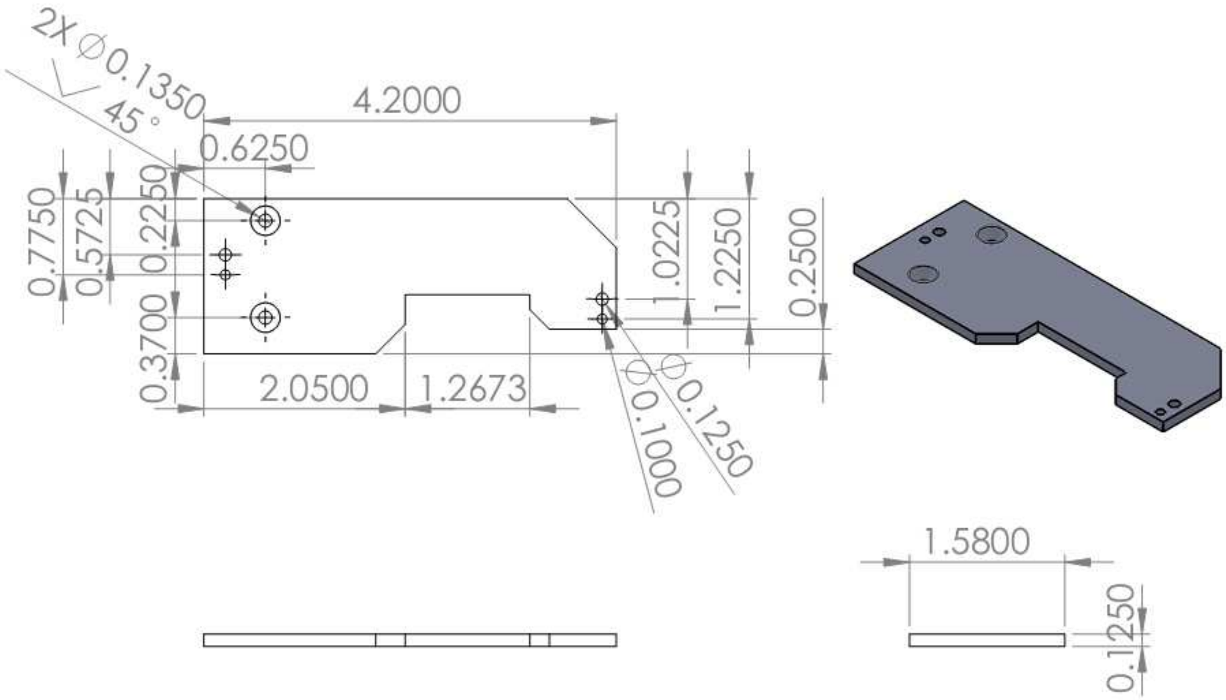
The following drawings show how to dimension the various components that I machined for the electric car and the parallel hybrid car. Note that the exact dimensions may vary based upon their actual mating location on the car.

C.1 Electric Motor Mounting Plate



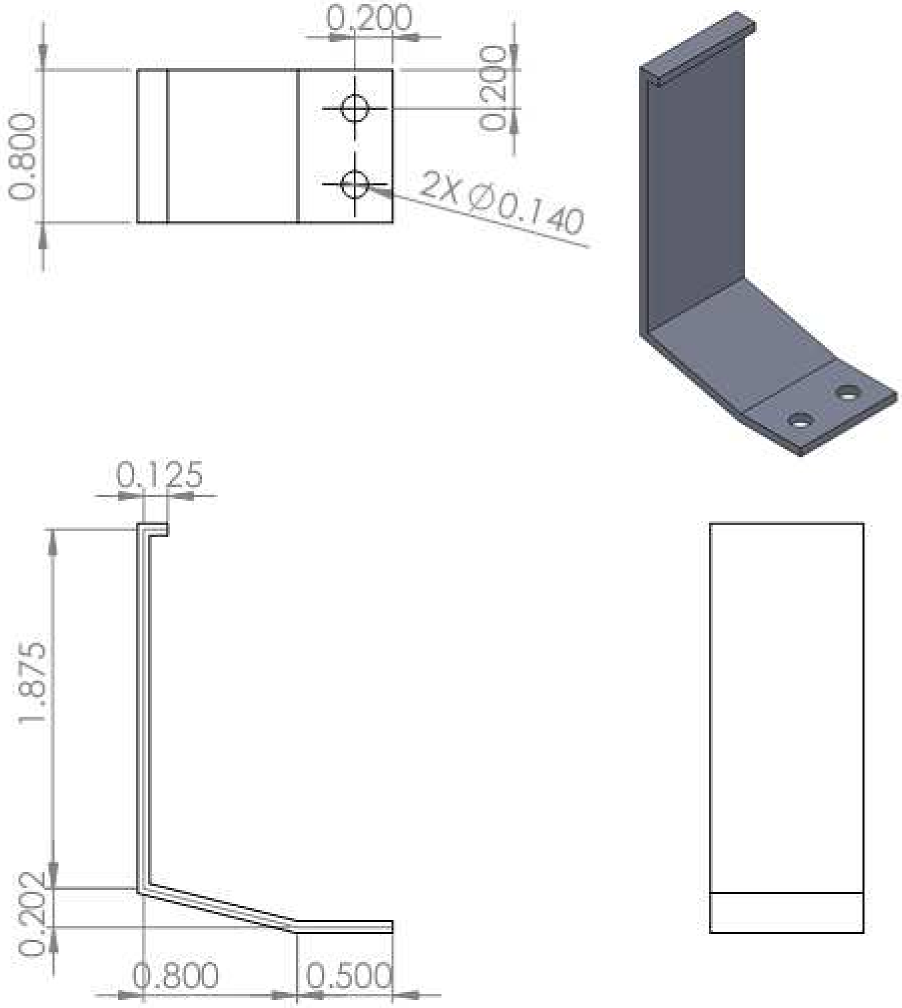
C.2 Fuel Tank Mounting Plate

Note that the fuel tank that I machined for the car had a significantly different geometry. However, the functional features were in the same relative locations.

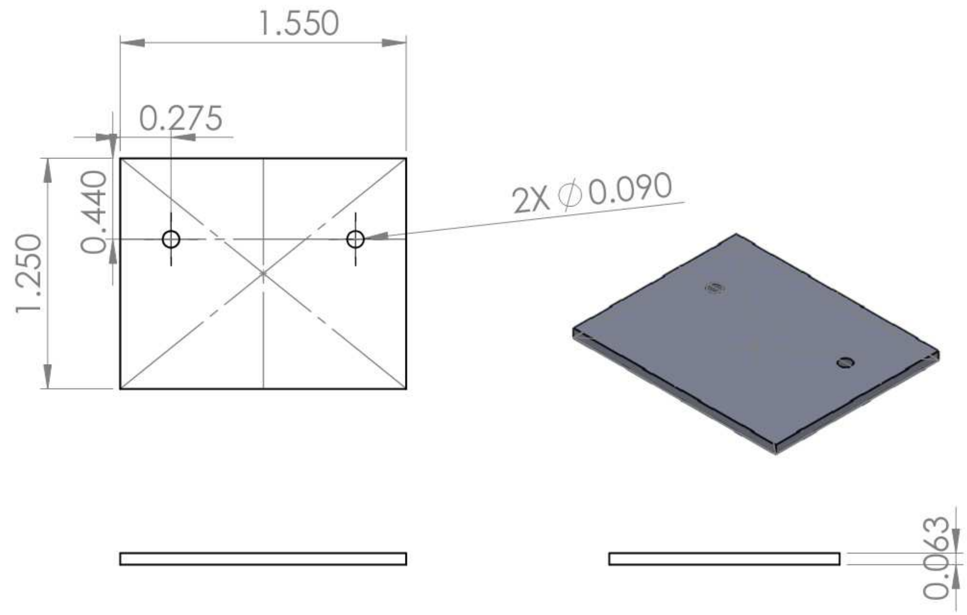


C.3 Battery Clip

The location of the holes in the battery clip vary depending upon the location of the corresponding holes in the plastic chassis extension.



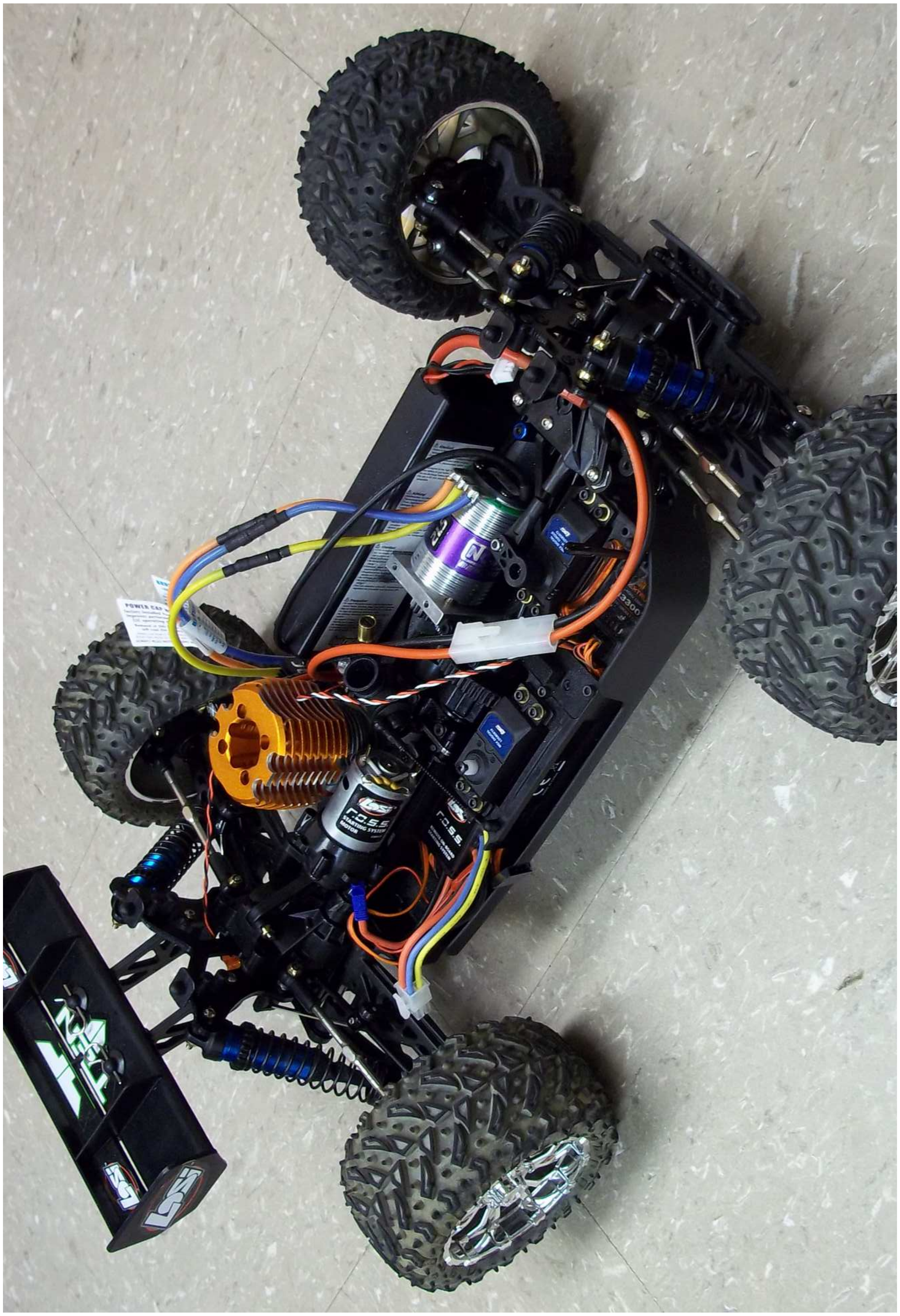
C.4 ESC Mounting Plate



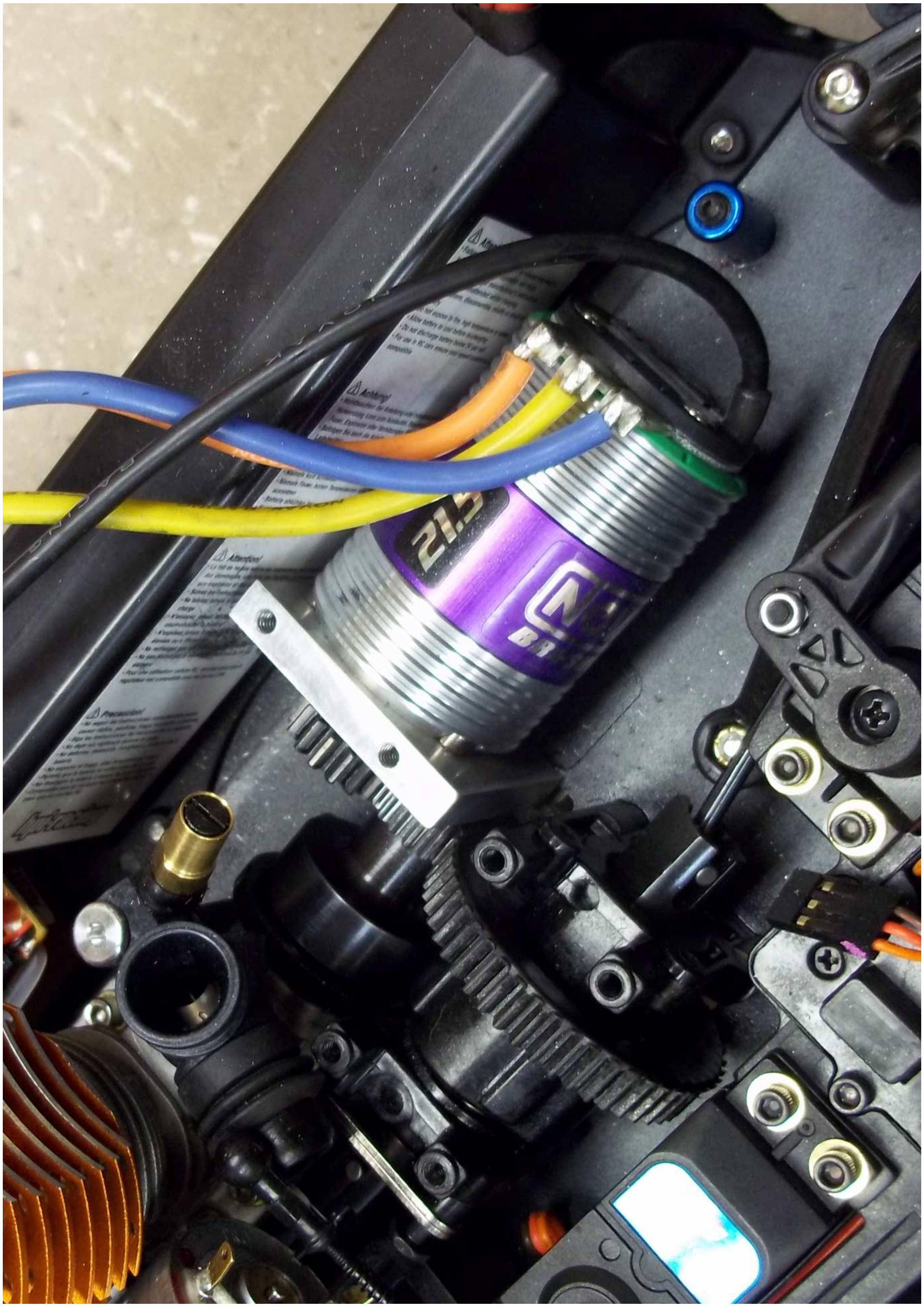
D Additional Photographs

D.1 Electric Car

D.1.1 Alternative Angle of Electric Car

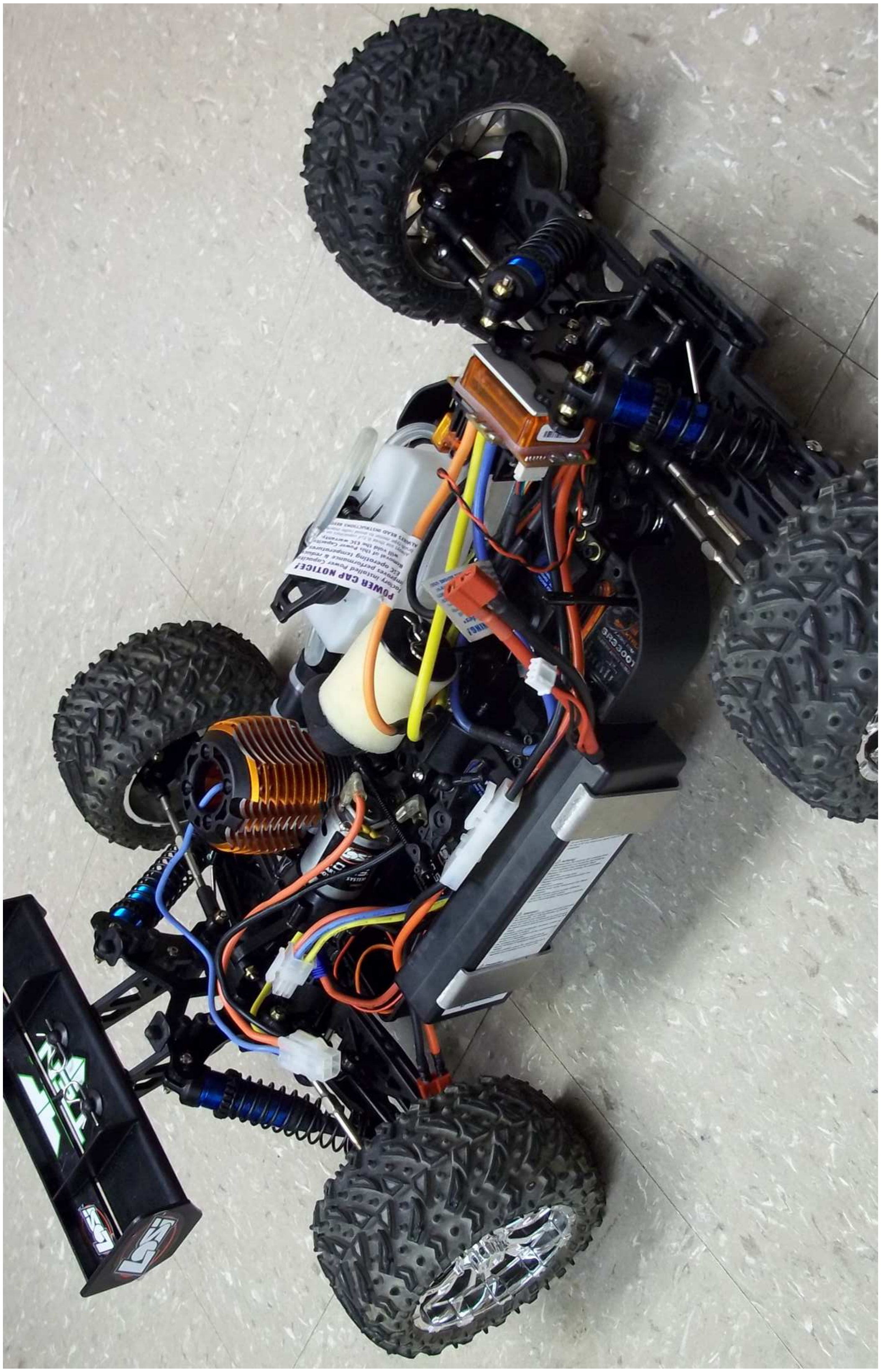


D.1.2 Close-up of Electric Motor Mounted on Chassis

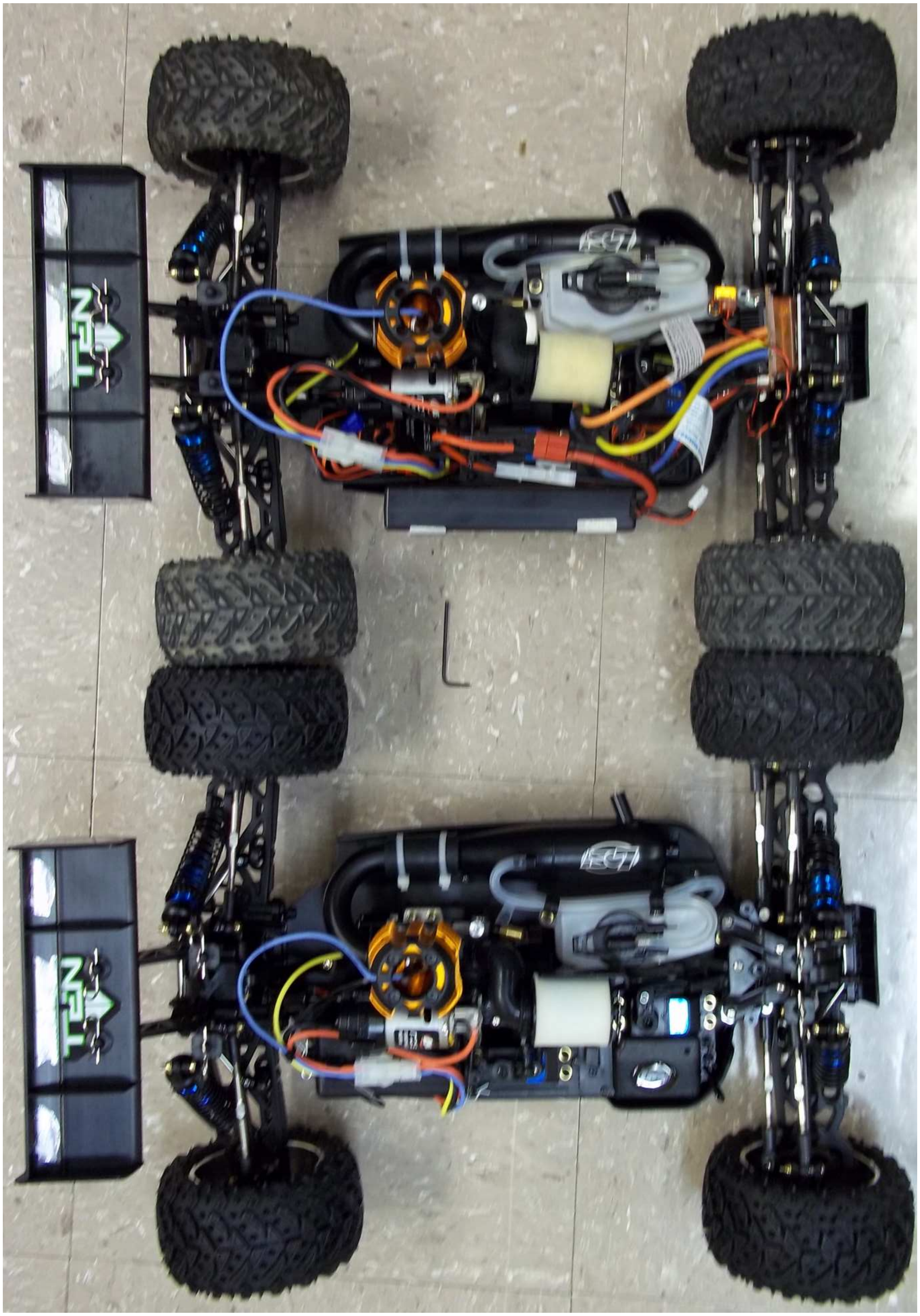


D.2 Parallel Hybrid

D.2.1 Alternative Angle of Parallel Hybrid



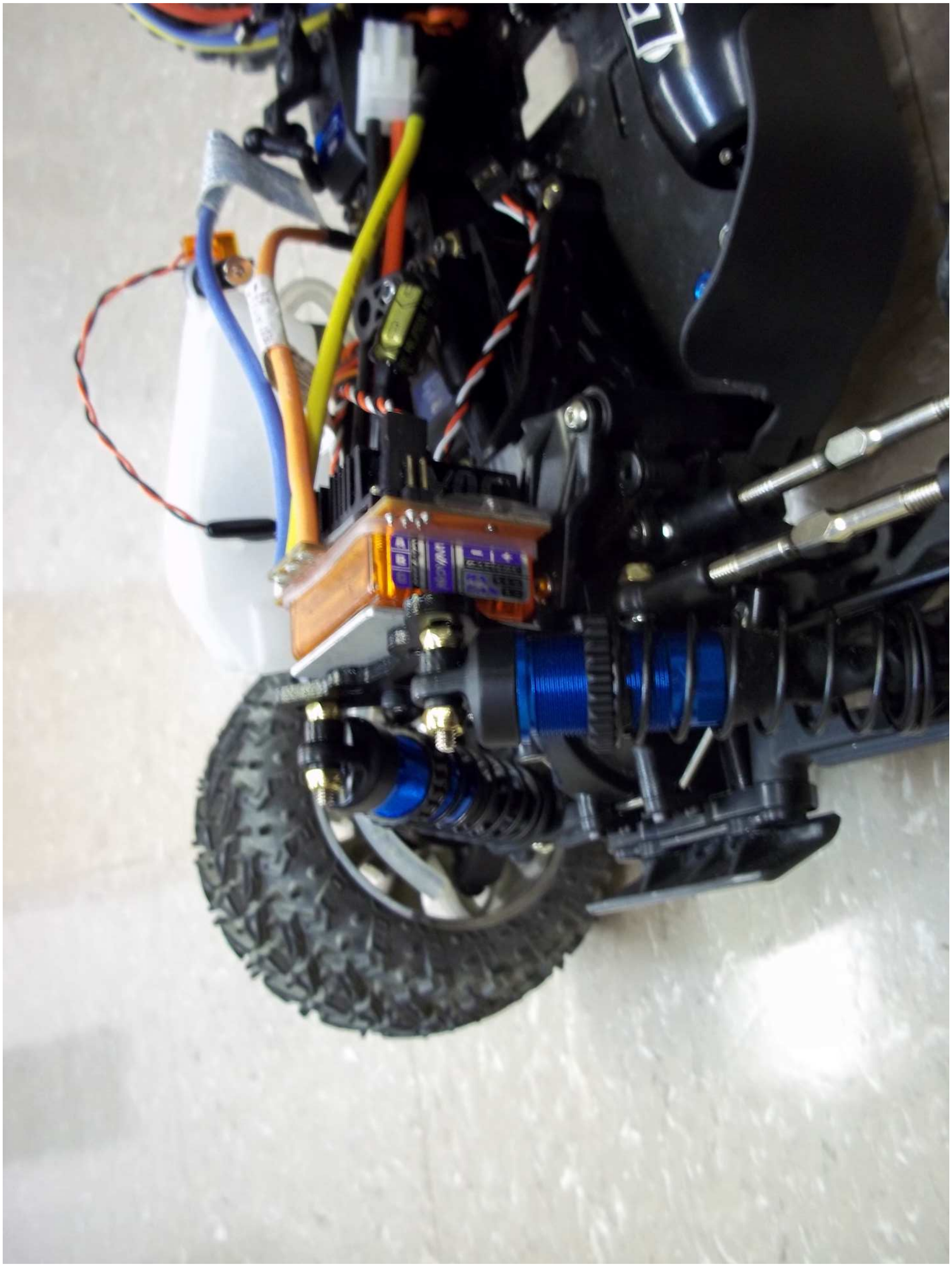
D.2.2 Comparison of All-Nitro and Parallel Hybrid Cars



D.2.3 Fuel Tank Mounted in Car

D.2.4 Close-up of Battery Clips

D.2.5 ESC Mounted in Car



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EDUCATION

The Pennsylvania State University | **University Park, PA** | **05/2012**

- B.S. in Mechanical Engineering
- B.S. in Nuclear Engineering
- Schreyer Honors Student
- Dean's List 7 semesters

RELEVANT EXPERIENCE

PSU MNE Department | **University Park, PA** | **10/10 – 05/12**
Research Assistant

- Designed and constructed hybrid RC car using appropriate sensors and controllers
- Designed and machined custom parts for car
- Interacted with suppliers to solve problems and select appropriate parts to purchase
- Working to develop child-safe RC car kit with swappable components that allow the car to run on gas, electricity, or both as a series, parallel, or power split hybrid

Westinghouse/Penn State University | **University Park, PA** | **06/11 – 08/11**
Toshiba-Westinghouse Undergraduate Fellows Program

- Computationally investigated secondary fluid flow through a 90° pipe bend using the ANSYS suite
- Coordinated computations with concurrent experimentation in order to make direct comparisons
- Prepared a report and a poster, and gave a presentation to Westinghouse executives

PSU Office of the Physical Plant | **University Park, PA** | **09/09 – 11/10**
HVAC Commissioning Engineer Internship

- Saved PSU $60,000 per year in energy use, reduced university coal use by 82 tons per year, and reduced CO_2-equivalent emissions by 377 tons per year by implementing appropriate energy-saving technology
- Developed data processing mechanism in Microsoft Excel to eliminate cumbersome manual work
- Prepared numerous commissioning project reports
- Helped coordinate co-departmental project including effectively delegating tasks to other workers
- Learned and used AutoCAD to modify and create building plans

INDEPENDENT HONORS PROJECTS

Honors Project in Reactor Physics

- Developed Java Applet to model the radioactivity of nuclear waste over time
- Successfully implemented a dynamic, multivariate 4^{th}-order numerical method

Honors Project in Mechanical Vibrations

- Successfully determined the pedaling energy losses in a bicycle suspension system
- Developed Simulink (MATLAB) program to model bicycle system

Honors Project in Gas Turbines

- Performed a literature review to investigate the effects of turbine blade cooling on thermal efficiency
- Prepared a report summarizing the results of the review

SKILLS

- Proficient in AutoCAD, ANSYS Fluent, SolidWorks, and Java
- Excellent troubleshooting skills
- Exceptional technical writer
- Experience interfacing with customers for website design

AWARDS AND ACCOMPLISHMENTS

Dr. John Karidis Award for Research Achievement in Mechanical Engineering	2011
Schreyer Academic Excellence Scholarship	2009 – 2012
Teaching Assistant for Reactor Physics course	Fall 2011
Featured Student in Annual MNE Department Newsletter	2011
IM Volleyball Team Captain	2009 – 2011
Freelance Website Design	2009 – 2012