Drive-by-Wire Go-Kart

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Abstract

This report summarizes the work accomplished by Emily Kan and Danielle Miller on the Drive-by-Wire Go-Kart. The motivation behind the project was to apply the concepts addressed in Mechanics of Solids, Digital Systems, Control Theory and other engineering courses to the design and development of an electric vehicle. The main idea was to design and construct a simple chassis in which the conventional mechanisms of steering, braking, and propulsion would be replaced with an electrical control system.

Introduction

X-By-Wire technology is based on the concept of replacing traditional mechanical control systems with electronics and electrical signals. The "X" stands for the various operations such as steering, braking, flying, and driving. This idea is becoming increasingly popular in the engineering industry because of the numerous benefits it offers in the engineering field and also within the environmental, political, and health sectors. The particular benefits of drive-by-wire technology are increased capacity for passengers, efficiency of manufacturing, absence of fossil fuels and decreased dependency on foreign fuel resources, and customization capabilities in terms of being able to implement different steering and braking apparatuses. The last type of benefit can be useful for handicap drivers who have limited or no ability to control a steering wheel and/or brake pedal.

For our E90 project, we decided to focus on drive-by-wire because it involves replacing the conventional mechanical methods of propulsion, steering, and braking with their electrical counterparts. The inspiration for our Drive-by-Wire Go-Kart is the General Motors *skateboard* design, introduced to the public in 2002.

Figure 1. GM skateboard design.

Source: http://www.autointell.com/nao_companies/general_motors/gm-autonomy/gm-autonomy-02.htm, March 2006.

GM combines hydrogen fuel cell propulsion with "by-wire" control (i.e. electrical control systems).[1] In GM's *skateboard* design, the functions performed by the standard combustion engine, with its sizeable cylinders and cumbersome fuel tank, are replaced by their electrical counterparts and crammed into a slim 13 ft long, 11 inch thick chassis. The steering and speed are all controlled by on-board electronics. The barebone structure of the skateboard introduces the idea of manufacturing a uniform operating system for all vehicles on which any type of shell and interior can be placed over it, effectively making customization of the shell and interior design a matter of personal preference rather than structural necessity. In addition to the general benefits of "by-wire" design mentioned earlier, it can easily be upgraded in terms of hardware and software whereas typical car designs now require much more manpower, time, and money to replace parts that may ultimately lead their owners to consider purchasing a new car rather than fixing the current one.

We also researched current work being performed at other colleges and universities to see how they have implemented by-wire technology into a working prototype. The Adaptive & Nonlinear Systems Laboratory (ANSL) at University of California, Los Angeles created the SMARTREV (Single-occupant, Multi-sensor, Actively-controlled, Remotely-tracked, Traction-adjustable Research and Education Vehicle) which is a prototype using "x-wire" control to implement braking, traction control, and steering. While similarities exist between our E90 design and the SMARTREV, our project is actually more similar to the prototype called E-Racer

[1] Source*:* http://www.cardesignnews.com/autoshows/2002/paris/preview/gm-hywire/
March 2006

created by Alex Kattamis et al. at the University of Connecticut[2]. The E-Racer is a joystick-controlled electric go-kart that essentially takes a joystick input and processes it through a microcontroller and outputs to the motors. The main difference between our design and the E-Racer is that the E-Racer prototype was designed specifically to the needs of person with cerebral palsy, so it is also fitted with a secondary control to be remotely controlled by a non-driver.

Due to time constraints and limited financial resources, we decided to restrict the focus of our project to designing a single-passenger chassis and system controls using a combination of hardware and software. The main goals of our E90 project in terms of system control were to control (1) propulsion, (2) steering, and (3) braking using an electrical control system.

The following report discusses the work and process entailed in taking our drive-by-wire go-kart from paper to prototype. We first discuss the vehicle design by explaining the design specifications needed to make the appropriate chassis and system component selections, then move onto the process of constructing and developing the chassis in the shop. Next, we discuss how we designed the electrical system for the kart and how we set up the network of electronics to communicate between the driver input and motors' outputs. We then describe the integration of the electrical system and chassis. We conclude with the qualitative and quantitative performance tests of the kart operation and suggest possible future work that can be done to improve the performance and design of the current model.

We have succeeded in designing a stable chassis with capabilities of all three system control functions we outlined in the beginning. Keeping in mind that technology is always being improved upon and being modified, we designed the mechanical platform and system control in such a way so that it can be improved and modified by those who work on it after us. Though we have reached the primary goals we initially set for ourselves, we have by no means reached the full potential offered by this E90 project. We leave it to future Swarthmore engineers to help realize these possibilities.

[2] Kattamis, Alex et al. *E-Racer, a Joystick Controlled Go-Kart*. Proceedings of the IEEE Annual Northeast Bioengineering Conference, 2001.

Vehicle Design

Chassis Design

In our initial design outline, we set out certain performance specifications we wanted to achieve, which would help guide our design. Generally, we wished to design and create a small, single-person electric vehicle to operate outdoors and navigate the college campus pathways. Noting that Swarthmore College is located in Eastern, but not coastal Pennsylvania, we recognized that the vehicle would not be designed to operate in harsh winter conditions, and that it would not be necessary to accommodate any other extreme environmental or climate considerations.

General Overview

The chassis was designed to accommodate a single passenger, the college pathways, the tricycle form, and other individual components (batteries, motors, control boards, etc.). It was necessary to adjust the original shape of the chassis to simplify mounting the motors so that they would provide forward propulsion (the original triangular frame would have complicated the task). ANSYS, a modeling and finite element analysis software tool, was used to estimate the deflection that frame members would experience based on variable member properties, such as size, cross-section, and material, and possible configurations and loading set ups. While a precise ANSYS model that fully characterizes the physical vehicle was not constructed, the modeling and analysis was used to sufficiently and effectively assess the design variables to minimize the deflection of frame members to less than a tenth of an inch in any member. The results of the ANSYS modeling helped inform our final chassis design as well as the various decisions we made during the construction process. The development and analysis of the chassis design using ANSYS is described in more detail in the following sections.

Design Development

Since developing a design for the chassis was comprised of four main parameters – frame material, member type, member configuration, and load placement – the first decision in the development of the chassis design was with respect to material. ASTM A-36 structural steel was initially selected for two reasons. First, in comparison to aluminum, steel is much stronger: the modulus of elasticity is E = 29E6psi for steel versus E = 10E6psi for common aluminum alloys. Also, in consideration of the actual construction of the chassis, machine technician Grant Smith, in his expert opinion, said that steel is much easier to weld than aluminum. However, all final

ANSYS modeling was all conducted using properties of aluminum T6061, since Mr. Smith decidedly purchased the materials for us over winter break.

For frame members, we agreed upon the use of square tubing with Mr. Smith, based on other go-kart models. The tubing is readily available in cross-sectional lengths of 1, 1 ½, or 2 inches and thicknesses of 1/8 up to 3/16 of an inch. Analysis began with the smallest (1" x 1" x 1/8") and was increased as needed to increase the second moment of area and reduce deflection. The arrangement of frame members took a triangular form to support the vehicle's tricycle design, but was adjusted to a rectangular base with tapered lengths in order to make mounting the motors easier (see preliminary sketches below).

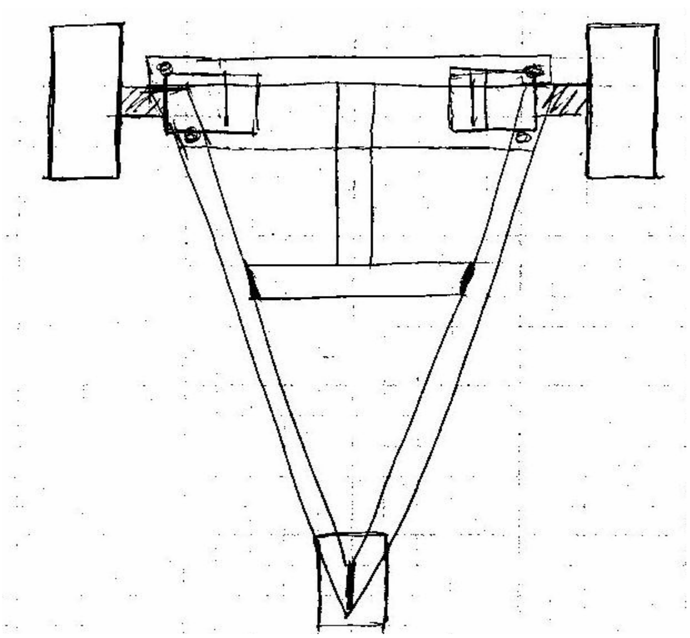


Figure 2. Original triangle frame design.

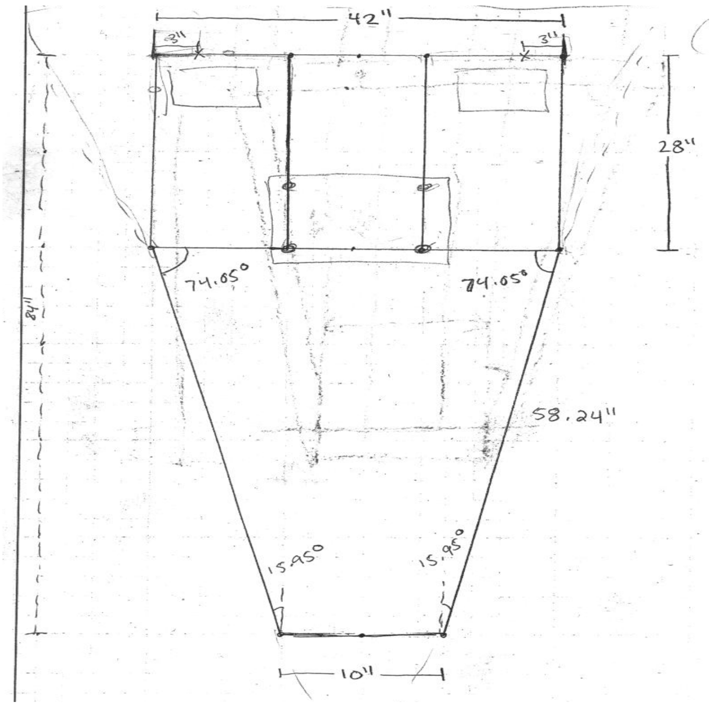


Figure 3. Revised frame design.

Cross-members were added to further distribute loading and thereby reduce deflection in heavily loaded members. We considered the width of the college pathways (between 6 ½ and 10 ½ feet at any point) and the size, comfort, and safety of the driver in determining the chassis width, which was set at 42 inches. The overall length of the vehicle, set around 7 feet, was chosen in order to accommodate taller drivers and to aid in the distribution of loads.

The distribution of weights, or loads, was set for convenience, and for what was anticipated as useful application. That is, loads were distributed symmetrically to keep the center of mass centered and make the vehicle as stable as possible. The weight of the driver was placed at approximately 2/3 the length of the triangle form (measured from the tapered front end of the frame), since this is the center of mass of a triangle shape. Other loads, the motors and batteries, were placed to the rear of the driver, symmetrically along a wide base, to be balanced by the driver's legs and the front length of the vehicle.

To address the issue of safety, we intended to adjust or add certain features. First, the front end was redrawn as an additional member: a truncated front end instead of a pointed tip. A safety bar was also added to the design. The design of the safety bar was based on a review of go-kart and golf-cart designs, which were aligned with the intended use of this vehicle as a low-speed means of transportation or delivery. Images of such go-karts are displayed in Appendix A.

This type of roll bar wars represented in the ANSYS model. A mechanical brake was an additional safety feature, but we were not able to account for it in the ANSYS model.

ANSYS Modeling: Procedure and Results

As mentioned previously, the ANSYS modeling process was used to estimate the deflection that frame members would experience. The method of developing models in ANSYS is reviewed below, in which each of the following must be specified:

- Units
- Element type
- Element data
- Material Properties
- Nodes
- Elements
- Constraint loads
- Forces

One must also specify the number of Degrees of Freedom (DOF). The DOF references the relevant discipline being used for analysis, such as structural versus thermal analysis. To create a structural model, 6 DOF were used, three each to characterize structural displacement and rotation (Ux, Uy, Uz, and ROTX, ROTY, ROTZ). The British system of units using inches (BIN) was selected to match previous work, which had been conducted using such units (inches, lbf, etc.), and material properties were specified for the aluminum T6061 to be used. So, the modulus of elasticity was set to EX = 10E6 and Poisson's ratio to PRXY = 0.33.

The next item declared was the element type, which can be 2D or 3D. The element type was chosen to be able to “characterize the model's response” fully, without unnecessarily over-defining it[3]. The four characteristic shapes available are a point, line, area, or volume. The line element is a line with two or three nodes, which is used to describe beams. To develop a model of the chassis, BEAM188 was selected, because it is used for 3D applications and defined by two nodes, and a cross-sectional area can be specified.

Nodes were created and placed at distinct locations:

- Connections (where members meet)
- Restraints or Constraint Loads (where members are secured, i.e. expected location of wheels)

[3] *Help Menu*, ANSYS 9.0.

- Force Loads (where physical loads are applied)

Elements were defined and added to properly characterize the beams, and then constraint loads (restraints) and forces were applied at specified locations where they were expected to occur in the design. The final ANSYS element model can be seen in Appendix B, where the element type is also described in further detail.

The model was solved and various results were reviewed. Graphical data plotted the magnitude of deflection in frame members. Some of the resulting deformed shapes and nodal solutions that were reviewed are shown in Appendix B. Solution of the final model using aluminum T6061, 2” x 2” x 3/16” tubing, the configuration pictured in Appendix B, and the loading approximated at the nodes listed in the force list, as seen in Appendix B, showed that deflection would be less than a tenth of an inch. In fact, the greatest deflection was predicted to be 0.027 inches in the central member. Though we are confident in the predicted safety and structural soundness of the design, actually confirming this predicted deflection with measurable data was not within the scope of the project. We can, however, conclude from operation of the vehicle, that the chassis is stable, and it does not appear to deflect by any significant amount.

Specifications: System and Chassis Components

Design Specifications

We previously described general, physical performance specifications we set out to achieve with our design. With respect to system performance, we specified that the vehicle should operate at moderate speed, between 5 and 15 mph, for a duration of 1 to 2 hours along flat terrain, and accelerate from 0 to 4 mph in 6 seconds (we conceded that for the purpose and use of the vehicle, a better acceleration time would not be required; we hoped this would help reduce the cost of the motors by reducing the demand for torque and power). Operating along the college pathways requires ascending and descending hills, so we determined from consulting topographical maps of the campus (obtained from Facilities Management, contact: Mike Boyd) that the steepest slope is between 9 and 11 degrees (occurring behind McCabe Library and Willets Dormitory). To insure that almost any student in the Engineering Department and most faculty and staff would be able to ride and operate the vehicle (since we hope other students will pick up and continue work on the project), we specified that the vehicle should support a driver weighing up to 250 lbs and the roll bar should provide clearance for a driver up to 6 1/2 feet tall.

The original vehicle performance criteria were established to reflect our goals for the vehicle's operation and to guide our design of the electrical system. They are shown below:

Table 1. Vehicle Performance Criteria

Speed Range	5-15mph
Time Duration	1– 2hrs
Hill Grade	16-20% grade

Motor Selection

Consideration of the design specifications guided primarily our selection of DC motors. Sizing the motors was determined by four criteria: stall torque (τ_{stall}), continuous torque (τ_{cont}), no-load speed (ω_o), and continuous speed (ω_{cont}). The figure below shows a torque - speed curve, which is used to describe the performance of an electric motor.

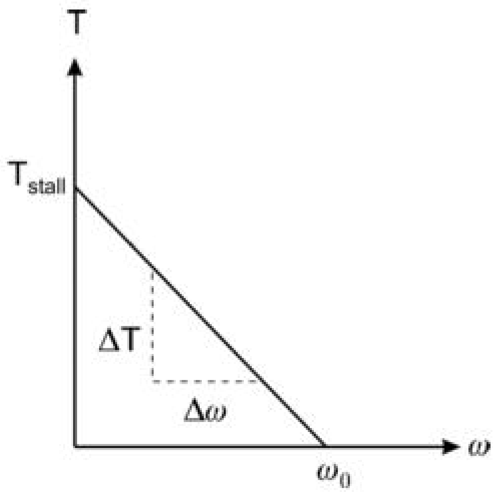


Figure 4. General torque - speed curve.

Source: http://www.20sim.com/webhelp4/Toolboxes/mechatronics/Servo_Motor_Editor/Theory/Torque_Speed_Plot/General_Model.htm, March 2006.

The figure below also plots a theoretical loading; the area under the curve is the power produced and the maximum load power is specified with a red dot.

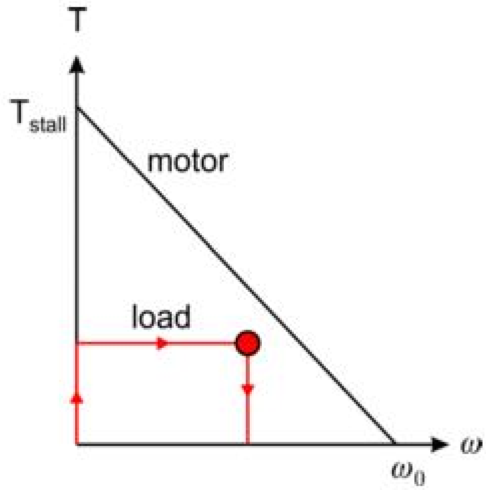


Figure 5. Torque – speed curve showing the torque required for a theoretical load. "The red dot indicates the point of maximum load power."
Source:
http://www.20sim.com/webhelp4/Toolboxes/mechatronics/Servo_Motor_Editor/Theory/Torque_Speed_Plot/General_Model.htm, March 2006.

Before we could assess the torque – speed characteristics to look for in a motor, it was first necessary to determine the laden vehicle weight (the total load from the chassis and all other vehicle components including the driver), which required a detailed projection of all component weights. General background research on go-karts, scooters, and golf carts helped provide a basis for thinking about the loading and power requirements. Professor Orthlieb was also consulted to help provide an estimate for these loading values. A breakdown of estimated loads is listed in the following table:

Table 2. Estimated vehicle loads in units of lbm. (Estimates are high end values.)

1. frame	square steel tubing, 1/8" wall	75
2. other frame pieces	aluminum	30
3. wheels/tyres	2 15lb driving wheels (10" diameter, 3 1/2" base, pneumatic, light tread from Smitty or 18" diameter), 1 10lb freely rotating wheel	40
3. motor x 2	brushed dc electric, series or traction	60 – 100
4. battery (1-2)	lead acid, deep cycle	100– 200
5. single passenger	maximum allowable load of the driver	250
6. sensors and controllers		15
Estimated Total	estimated maximum laden vehicle weight, to be used for motor sizing calculations	700

Having estimated the maximum laden vehicle weight and determined the steepest grade hill on campus, we were then equipped to design for the 'worst case scenario,' that is, the propulsive force required to accelerate a 250 lb driver (with the vehicle) from rest up an 16-20% grade hill at 4mph. The force of propulsion breaks down into three forces: rolling resistance, grade resistance, and linear acceleration, as seen in the equation below:

Equation 1. $$F_{prop} = F_{rr} + F_{gr} + F_{la}$$

Professor Orthlieb also helped guide us in these estimations, which were based on a combination of physical calculations and referenced values.

To estimate the force due to rolling resistance (F_{rr}), a "Table of Rolling Resistance for Various Materials"[4] was consulted, as well as an equation using the typical estimate for the coefficient of friction (u_{rr}) of radial ply tires[5], a tire design used on most vehicle and bicycle tires. According to the table, the rolling resistance (F_{rr}) is estimated as 12 lbf on "good asphalt" or 15 lbf on "good macadam" per 1000 lbm gross vehicle weight. Using the equation:

[4] "Table of Rolling Resistance for Various Materials." *Webtec Products Ltd*, March 2004. Source: http://www.webster-inst.com/techinfo/equation/eqnfr/eqn16.htm, March 2006.
[5] Larminie & Lowry, Electric Vehicle Technology Explained. Wiley, 2003.

Equation 2. $F_{rr} = u_{rr} \cdot m \cdot g$, $u_{rr} = 0.015$

we found F_{rr} to be 11 lbf. Since the table estimate for the rolling resistance force is based on a 1000 lbm gross vehicle weight, and our high estimate for this value is 700 lbm, it is reasonable to take the lower estimate for rolling resistance – 11 lbf or approximately 49N. This also serves to help reduce the cost of the motors by reducing the torque and power required.

We used two methods to approximate the force due to grade resistance. The first was a method from Webtec Products Ltd, the website where we reviewed rolling resistances, which applies the percent grade of the hill (the slope of the hill expressed as a percentage) to approximate the force due to the laden vehicle weight that must be overcome. This method is given in the following equation:

Equation 3. $F_{gr} = (\textit{gross vehicle weight}) \cdot (\frac{\%\ grade}{100})$

where the gross vehicle weight is taken to be 700 lbm (318kg) and the grade is 16-20%. For calculations, we employ the 18% grade (equivalent to an angle of 10.2°). This yields F_{gr} = 126 lbf (560 N).

The second calculation used to estimate the grade resistance force was based on the analysis of the vehicle's free body diagram on the hill. The diagram below shows the three forces ($F_{rr}, F_{gr}, F_{la} = m\ddot{x}$) acting on the vehicle when climbing a hill.

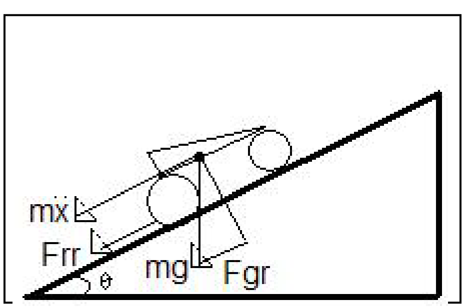


Figure 6. Diagram to illustrate the forces acting on the vehicle when climbing a hill.

The resulting equation for grade resistance is:

Equation 4. $\mathrm{F}_{\mathrm{gr}} = m \cdot g \cdot \sin\theta$

For θ = 10.2° (the equivalent of an 18% grade), F_{gr} = 124 lbf (552 N). Averaging the results of the two methods yields the following estimate: F_{gr} = 125 lbf (556 N).

To determine the force to linearly accelerate the vehicle, we first decided it would be sufficient to reach 4 mph in a few seconds, given the vehicle's moderate operational expectations. 4 mph is equivalent to about 6 ft/second, so to simplify the calculation, we set the desired acceleration (a) to achieve 6 ft/sec. (4 mph) in 6 seconds, so, a = 1 ft/s^2.

Taking the high estimate for the vehicle weight, 700 lbm (318kg), the force of linear acceleration, $F_{la} = m\ddot{x}$, is 22 lbf (97 N).

All together then, the force of propulsion can be calculated using Equation 1, so:

F_{prop} = (11 + 124 + 22 = 157) lbf = (49 + 552 + 97 = 698) N.

Having determined the propulsive force required, we needed to estimate what size tires with which we would outfit the vehicle in order to calculate torque, since $\tau = F \cdot r$ where r is the tire radius. Based on our background research with golf carts and go-karts and our interest in minimizing destruction to the grass when driving across the lawn, we wanted to select tires with a wide tread. We anticipated using tires up to 16 or 18 inches in diameter (according to our research, this is the minimum tire diameter to obtain a tread width of 6 to 8 inches). As a result, the stall torque, which is the torque a motor would produce at ω = 0 rpm, was calculated as follows:

$$d_1 = 16''; r_1 = 8'' = 0.67\,ft \quad OR \quad d_2 = 18''; r_2 = 9'' = 0.75\,ft$$

$$\tau_{stall} = F_{prop} \cdot r\ , \quad F_{prop} = 157\ lbf\ (698\ N)$$

$$\Rightarrow \tau_{stall,r_1} = 105\ lbf\ (142\ Nm, 1260\ inlb) \quad OR \quad \tau_{stall,r_2} = 118\ lbf\ (160\ Nm, 14160\ inlb)$$

Since the vehicle will have two independent motors for rear wheel drive, the torque required of each motor is just half of the total. Thus, based on a 16" diameter tire, the stall torque per motor would be: $\tau_{stall\ per\ motor} = 52\ \ ftlb\,(71\ Nm, 636\ inlb)$.

Continuous torque, given in the equation below, is the torque required to overcome rolling resistance; grade resistance is negligible and the vehicle is already accelerated.

Equation 5. $$\tau_{cont} = F_{rr} \cdot r$$

Then, based on a 16" diameter tire, the continuous torque per motor would be: $\tau_{cont\ per\ motor} = 4\ \ ftlb\,(5.5\ Nm, 48\ inlb)$.

After calculating the torque specifications, we reviewed and revised our design criteria for speed. We had to specify the no-load speed - "the maximum speed of the motor at no load when the voltage that is required to produce peak torque is applied" [6] – and the continuous speed – the average speed at which the motor will operate. When establishing what values of no-load speed (ω_o) and continuous speed (ω_{cont}) would be required, we again conceded to the moderate design specifications with respect to speed and designed for ω_o = 12 mph, which is about 250-260 rpm, and for ω_{cont} = 4 mph, which is about 80-90 rpm. Table 3 below summarizes these motor sizing calculations.

Table 3. Single motor criteria determined from design specifications.

Stall Torque (in-lb)	Continuous Torque (in-lb)	No load speed (rpm)	Continous speed (rpm)
630	48	257 (12mph)	86 (4mph)

Research was conducted to find a DC motor model that would meet these specifications. We consulted with the following companies: Groschopp, Kollmorgen, Exonic Systems / Applied Motion, PML, Leeson, Pittman, NEE Controls Ltd / Cleveland Motion Controls, Bueler, Faulhaber, L.M.C. Ltd / LEMCOLTD, Grainger, Bodine Electric Company. We realized that

[6] Source: www.servomag.com, March 2006.

some of these companies specialize in application-specific motors (like stepper motors), so they did not have anything to offer for our needs.

We concluded that we needed a gearhead motor to achieve the torque specifications, but we discovered that even gearhead motors do not often reach such high torque outputs. Therefore, it was necessary to make additional concessions in our motor specifications. If we considered the high-end weight estimate and conceded some performance specifications (i.e. ascend the steepest hill not from rest but already at some velocity, or, allow that we only ascend the smaller hills: about 6-8 degree angles), it was possible to reduce the torque demand by up to about two-thirds. Selecting a gearhead motor also reduced the amount of construction, since we would not have to size and install the gearing.

We considered seriously various options from Groschopp, Kollmorgen, and Exonic Systems / Applied Motion. At Groschopp, we consulted with Ed Tullar, who was able to offer us some of the best options we could find at the most reasonable price available. We selected one of Groschopp's 24V DC gearhead motors (#56267). We were advised towards this one, because, should the load demand more torque and power than the motor could supply, the motor would cut out before tearing apart the gears. This motor is rated as follows:

Table 4. Groschopp motor speed and torque ratings.

Stall Torque (in-lb)	Continuous Torque (in-lb)	No load speed (rpm)	Continous speed (rpm)
444.80 lb-in	48.0 lb-in	250.8 rpm	--

Table 5. Groschopp motor efficiency ratings.

Gearbox:	84.9 %
Motor:	77.4 %
System:	65.7 %

Additional specifications can be reviewed in the product web page and data sheet, which are in Appendix C.

In summary, a brushed DC electric motor was selected for the low-cost appeal, and a permanent magnet gearhead motor was selected to supply the appropriate torque-current proportionality and the high torque values at lower angular velocities that the vehicle performance criteria required.

After the acquisition of vehicle components and the finalization of construction decisions, we took account of all anticipated loads and confirmed that the expected total, laden vehicle weight should be well under the estimated value (about 500 lbm versus 700 lbm). An updated inventory of vehicle loads is listed in Table 6.

Table 6. Updated vehicle load values and estimates in units of lbm.

1. frame	square aluminum tubing, 2” sq., 3/16” wall; aluminum plating	76
2. other frame pieces	aluminum, steel	20
3. wheels/tires (3)	2 driving wheels (two 13” diameter turf-savers, one 8” diameter castor)	35
3. motors (2)	2 brushed dc electric, gearhead	30.2
4. batteries (2)	2 sealed lead acid, deep cycle	66
5. single passenger	maximum allowable load of the driver	250
6. sensors and controllers	negligible	5
Estimated Total	estimated maximum laden vehicle weight, to verify motor sizing calculations	483

It was also noted that the final tires selected for the drive wheels have a diameter of about 13 inches, not 16 or 18 inches, as had been originally proposed. As a result, the torque demand was further reduced, and we confidently dispelled any concern that the motors would not be able to propel the vehicle. A table that summarizes and allows comparison of our initial design specifications, the Groshopp motor specifications, and our updated design specifications is shown below.

Table 7. Initial design, Groschopp motor, and updated design specifications.

Design Specifications	**Torque per motor (in-lb)**		**Speed (rpm)**	
	Stall	**Continuous**	**No-Load**	**Continuous**
Initial	630	48	257	86
Motor	445	48	251	--
Updated	390	36	317	106

Battery Selection

Initial research indicated that we would want deep cycle, or marine, batteries that discharge a steady amount of current (capable of small surges) over a relatively long period of time. In other words, they discharge deeply and repeatedly – what we need for the vehicle's operation. Sealed lead acid (SLA) batteries were chosen for a few reasons. First, they are relatively inexpensive, compared to nickel metal hydride (NiMH) batteries, for example, and we can afford the trade-off with the additional weight (SLA are heavier than NiMH). Another distinguishing feature of SLA batteries is the low internal resistance, which means that voltage does not fall off a lot when current is drawn (Larminie 2003, p30).

A 24V system was chosen to support the vehicle propulsion system: motors and motor controllers. It is also noted that the amount of voltage is not considered harmful to a human being in case of an accident. Because of restricted person-power, it was decided that two 12V batteries would be optimal (so they can be easily moved and positioned). The use of two 12V batteries, which each weigh less than a 24V battery, made it possible to distribute the weight more across the chassis (meaning the load is less concentrated), thereby reducing the stress ($\sigma = \frac{F}{A}$) experienced by the loaded members. Plus, 12V batteries are readily obtainable.

The SLA batteries also support our interest in making the life-cycle of the vehicle 'environmentally friendly,' because according the *Battery Council International*, 98% of lead and plastic from lead acid batteries is recycled, and new batteries feature 60-80% recycled lead and plastic. Lead acid batteries also support the US lead industry, consuming more than 80% of lead produced in the US (*BIC*).

Motor Controller Selection

We selected the KBBC-24M motor controller from KB Electronics (pictured below), for one, because the Groschopp motor company uses their products. Secondly, the motor controller was sufficient for the system requirements; it is the 24V DC chassis model, it can operate between 10 and 80A, it uses a PWM output, and it has forward/reverse/stop and speed inputs. It also features adjustable trimpots that allow the user to set the rates of acceleration and deceleration, the maximum forward and reverse speeds, and a current limit setting, which is an especially attractive aspect of the controller, because it assures that the user will not burn out the motors. In general, this controller offered us a more robust model at the most reasonable price based upon our research. The product manual and description are in Appendix D.

Figure 7. Image of KB Electronics KBBC-24M motor controller.

Microcontroller Selection

For our system control design, we decided to use the PIC16F877 microcontroller (Programmable Interrupt Controller) integrated onto a PICDEM 2 PLUS Board and used the PIC-C compiler software to program the algorithm we created. The PIC is powered by a 9V battery that can be plugged into the board. The reasons why we chose this particular microcontroller and board are its availability in the lab and our familiarity with the programming language, software, and hardware. The PIC board has multiple ports to which we can attach inputs from the joystick and any other additional inputs such as sensors to be relayed to the microcontroller, and it also has a mini-breadboard configuration to include extra electrical components.

Figure 8. Image of PICDEM 2 PLUS Board and microcontroller.

Tire Selection

The tires we chose for the drive mechanism are 13” X 5.00” tires with 6-inch diameter rims from Surplus Center. They have a maximum pressure of 20 PSI. The hub has a ¾” bore x 4” wide hub. The ¾” bore was chosen to match the ¾” drive shaft of the motors (going along with our original plan to implement direct drive). We considered many other tires, some for their direct drive assembly (when we were still considering direct drive) and some for their size (see Appendix E for this and other tires considered). We wanted to choose tires that had a diameter large enough to give the kart a clearance between 5 and 10 inches above ground, in fact there is an 8-inch clearance. We decided that the tires needed to be pneumatic so that there would be some give in the tread when going over uneven surfaces in the road, making the ride smoother than if we were to use plastic non-pneumatic tires. The pneumatic tires also offer more traction with the road than other models do. The selected tires were also relatively inexpensive.

Safety Features

Roll Bar

As with any transportation vehicle, we needed to implement safety features to protect the driver from incurring any injury as a result of operating the kart. In the design stages of the kart we looked to the basic devices used on go-karts and automobiles. We included a roll bar design which would protect the driver in the case of a rollover, i.e. the driver goes around a bend too quickly and causes the kart to flip over sideways.

The original design of the roll bar was a single horizontal bar supported by two vertically slanted bars (see figure below). The rollover bar apparatus was to be positioned on the rearmost frame member because commercial go-karts had a similar design, but it was then decided that the rollover bar apparatus would be most effective if moved up towards the middle of the frame so that it passes over the driver’s head, with each vertical bar on each side of the driver. Since part of the rollover bar passes directly above the driver, we had to be sure that the height of the bar was high enough to clear the driver’s head. When deciding how high the rollover bar should be, we decided that the maximum height of a seated driver would be approximately 42 inches, so we designed the height of the bar to be 42-inches high from the frame of the kart.

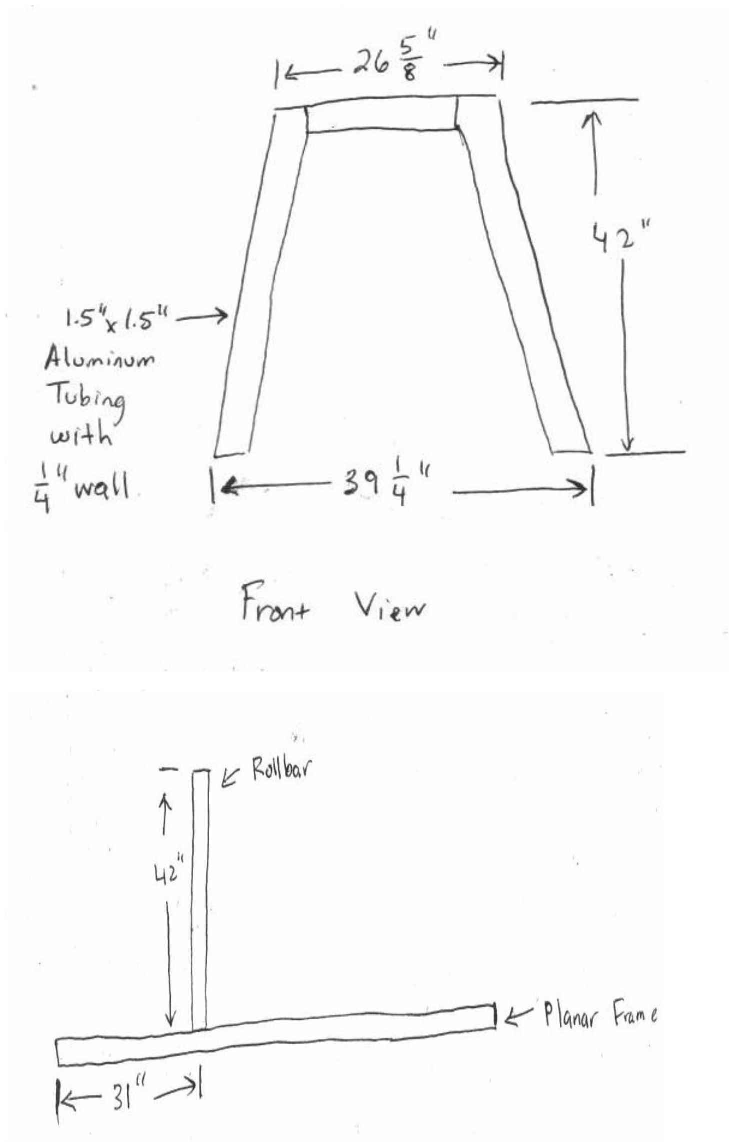


Figure 9. Roll bar design Front View and Side View

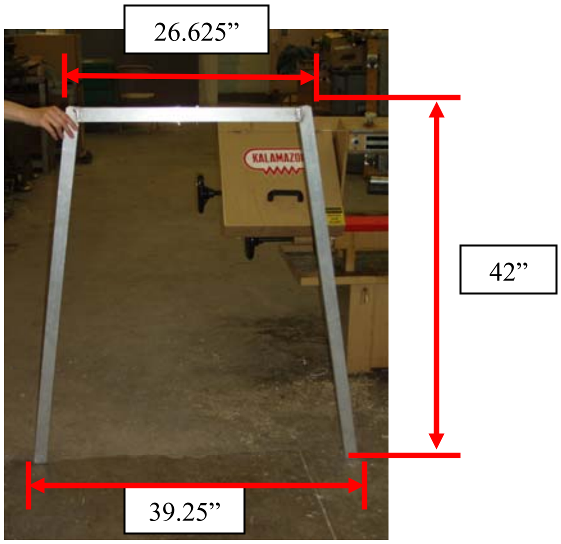


Figure 10. Actual roll bar constructed for our go-kart

When the roll bar was finally constructed and placed over the kart, we realized that the roll bar was quite high and would prove to be unstable when the kart was being operated. We redesigned the roll bar so that it has a tripod setup: the main bar apparatus passing over the driver’s seat and supported by a third bar (extending to the rear of the kart) to keep it from tilting forward or backward. So the only part of the roll bar we modified was how it was to be supported on the kart and not the specified height or width. However, due to time constraint and reconstruction to the shop environment, which ultimately led to pieces of the roll bar being lost, so it was not possible to complete the modification, and the roll bar was not implemented on the kart.

<u>Seatbelt and Protective Gear</u>

We initially planned to have a seatbelt for the seat, thinking that it would be necessary to keep the driver from falling out of the kart (in the case that a rollover occurs or the vehicle experiences abrupt movement). The design for attaching the seat belt avoided having to drill more holes in the critical members of the kart frame, by using the existing holes used for the seat apparatus, so we decided to have a simple belt that would go across the waist of the driver. This would prevent the driver from slipping forward and backward while the kart is moving and changing directions. In the end, we felt it was not in the best interest of the driver to have a seatbelt without a roll bar installed. In addition, we concluded that the kart speeds would be low enough for the driver to operate safely without a seatbelt.

Without the implementation of the roll bar and the seatbelt, we had to make sure that we had a safety measure to protect the driver from injury, so we required the driver to wear a helmet and kneepads while driving to ensure that hair does not get caught in the drive chains behind the seat and to provide additional head and leg protection in the unlikely case of rollover.

Mechanical Brake and Kill-Switch

Another set of safety features we introduced were a mechanical brake and an electrical kill-switch. These parts were added to the kart as alternatives for the driver in the case there is an electrical failure in the system. In the instance that the system control malfunctions and the motors no longer respond to the speed and/or direction inputs indicated by the joystick, the driver can engage the emergency mechanical brake.

The emergency brake of the kart is similar, in some respects, to the parking brake found in a standard car. Unlike the complicated emergency brakes in cars, the simple brake we designed and constructed involved pressing a PVC block directly on the tire. In a typical car, braking involves hydraulics and friction pads that are pressed onto a brake drum – nothing is actually pressed onto the tread of the tire. When the plunger is engaged, the rod is thrust backwards, pressing the PVC against the tread surface of the tire. The advantages to this design are the ease of building and implementing it on the kart. The setback to this design is that the repeated or heavy use of the brake may wear down the rubber tire treads and cause the kart to go into a circular path because it is only implemented on the right wheel; however, the latter argument is only a minor issue if considering the conventions of U.S. traffic directions – the kart would not be swerving into oncoming traffic lanes – we would expect it to veer off to the right. The kart is also not a racing vehicle, so we are not expecting to travel at very high traffic speeds, so wear on the tires should not be significant during normal operation. In the instance where there is considerable wear on the current tires, two spare tires were bought to replace worn out ones.

The switch is dual purpose in that it serves as an on/off-switch in addition to being a kill-switch to the system. The switch is to shut off power to the system in the case of system control malfunction, such as the motor controllers setting the motors at a high, uncontrollable speed. In such a case it would be prudent to disengage the batteries from the electrical circuits. This would be helpful in preserving the motor controllers and motors from burning out because of excess current being passed through the circuits. The original switch we used was for 24V, 16A, because it was available in the lab, and there were no other switches capable of handling more current at the operating voltage. After a few experiences with sparks and burning wires, we decided to order an appropriate switch capable of handling the operating voltage and current of the system. The switch we decided upon is a simple 24V, 250A continuous (375A maximum) toggle switch implemented between the positive terminal of the battery and the positive terminals of the motor controllers. We made sure to choose the switch that could handle the maximum operating voltage (24V) and current (10A continuous, 80A maximum) to ensure that the driver is not hurt while using the switch.

Figure 11. Knob switch selected for our go-kart.

Vehicle Construction

The shop work involved as much design consideration as the theoretical design. One of the greatest challenges of building the kart was figuring out where to drill all the necessary holes in the frame members before having the machinist weld all the members together. This was somewhat of a chicken-or-the-egg problem because we needed to drill the holes without seeing the entire frame welded together. On the other hand, we could not proceed to drill the holes because it was necessary to align members and make sure holes in members were spaced apart appropriately; this we could not do unless we had the members welded together to restrict shifting of individual members. Needless to say, there were many hours devoted to planning the layout of all the holes in each member. As specific components developed and integrated during construction are discussed in the following sections, it may be useful to consult the completed assembly depicted below.

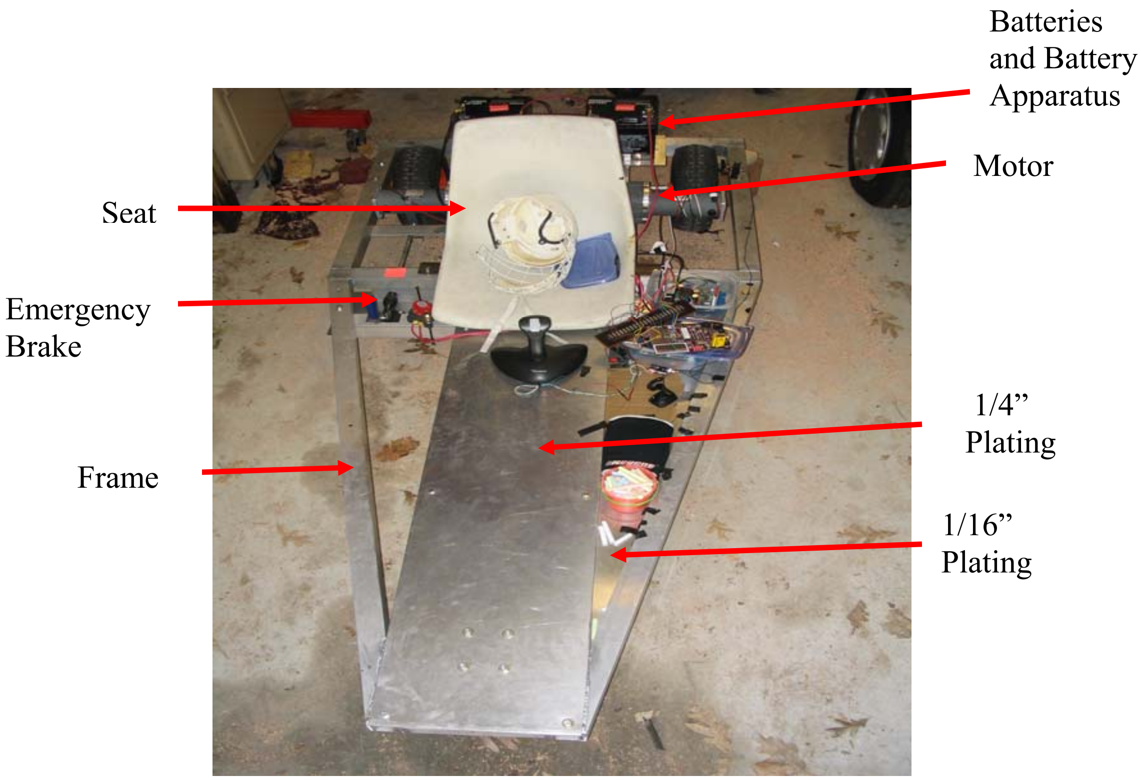


Figure 12. Assembled go-kart.

<u>Frame</u>

Although the basic shape of the chassis was set, it was also important to consider the deflection in the frame members. The frame members under the driver seat and the motors were considered to be the critical members, subjected to the greatest load, and thereby calculated to undergo the most deflection. In order to connect the motors, seat, and other components to the kart frame, we had to think about the direction, placement, and number of holes drilled into each frame member so as not to weaken the critical members. The final frame with holes laid out is illustrated in the figure below.

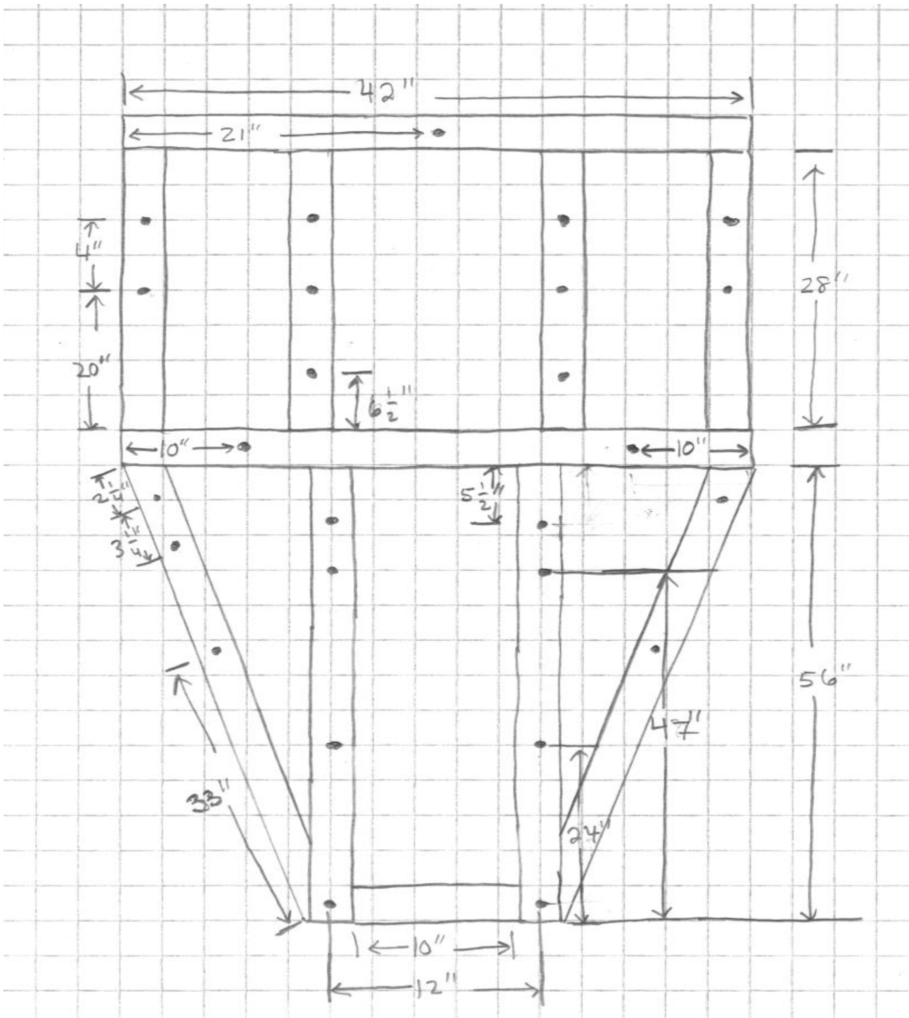


Figure 13. Frame design with layout of holes.

Seat

The seat we chose is a single piece of plastic with no perforations (this serves as a nice barrier between the driver's back and the drive system behind the driver. The curved shape of the seat was a bonus feature because it offered some comfort to the driver. We sawed off the steel legs, leaving only two horizontal bars (one across the front and one across the back) across which two 10" long plates were welded in a tic-tac-toe arrangement with the bars. To attach the seat to the kart, we created another tic-tac-toe shaped apparatus by welding the two 10" steel plates together with two other plates: a 24" and a 14" long steel plate (the 24" and 14" plate are parallel to each other). The 24" and 14" plates have holes drilled through them in order to attach it to the frame of the kart. Please see the sketch below.

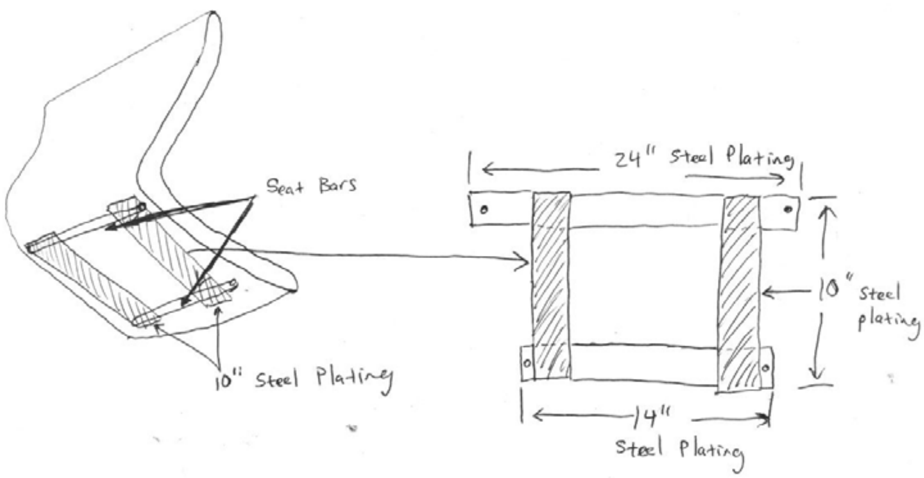


Figure 14. Sketch of seat apparatus.

Plates

Aluminum plating was used to cover the space in the front portion of the frame. A rectangular piece of 58" x 14" x ¼" aluminum plating is used to attach the castor wheel underneath and to serve as a platform for the driver's feet and the joystick. Two triangular pieces of 1/16" plating were used to form pockets on either side of the driver by attaching the plating underneath the frame. The pocket area is a holding place for the electronics. After preliminary testing, we found it convenient to have just the one triangular compartment; therefore, we did not attach the second one.

Battery Support Apparatus

We took advantage of Mr. Smith's suggestions in the design of this apparatus. Since we have two 33-lb batteries, we decided to support them over the intersection of the perpendicular members at the rear end of vehicle. The batteries are situated on a ¼-inch thick aluminum plating and clipped between 6" long, 3" x 5" angles in the back and a 14" long, 1" x 1" angle in the front. The batteries will be clamped down onto the plate with a single steal bar across the top and 4 all-thread bars running through the top steel bar and the bottom plate. This will prevent the batteries from falling off the kart when operating it, but it will also be easy to remove the batteries for recharging or maintenance.

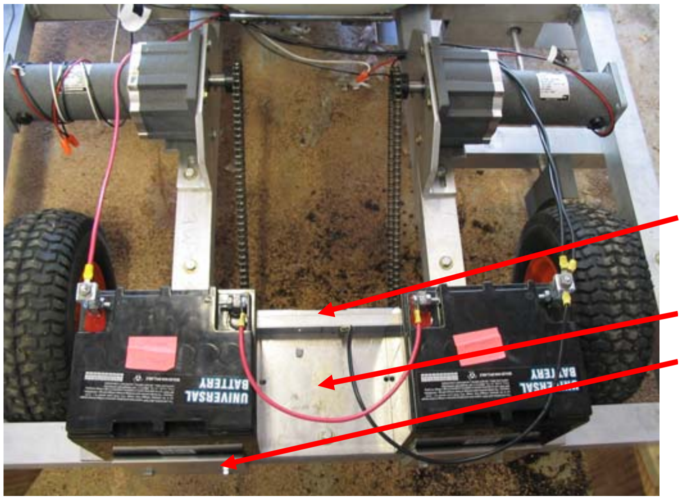


Figure 15. Battery support apparatus.

Motor Mounting

The motors are each attached to the frame via a 2” x 5” angles, each about 7 ½” long. The face of the motor is screwed into the 5” wall of the angle. The 2” wall of the angle has slots so that the motor can be adjusted in the forward and backward direction to adjust the tension in the drive chains. The motors are mounted to the topside of the frame to avoid contact with the tires and the ground.

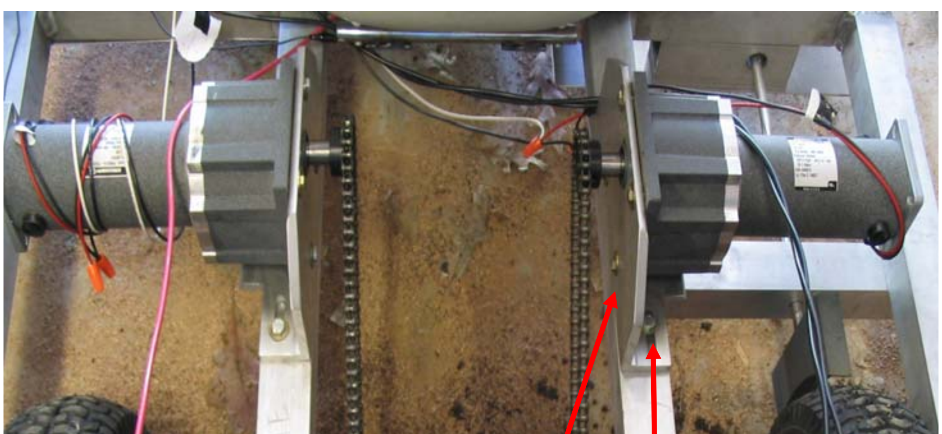


Figure 16. Motor mounting apparatus.

Mechanical Drive

Originally, we had designed the drive of the kart to be direct drive, that is, the motor shaft would be inserted into the hub shaft of the tire, and the key on the motor shaft would drive the tire through a keyway. We had to change this design, because the shaft of the motor is only 1.5 inches long, causing concern that the vehicle load on the motor shaft would be too great and could cause damage to the gears inside the motor. To solve this problem, we decided to implement the machinist's idea of using a sprocket-and-chain drive. In this design, pillow blocks are screwed to the underside of the frame members to attach the wheel and the drive shaft to the frame of the kart. The shaft passes through one pillow block, through the tire hub, and through another pillow block. A sprocket is attached to the motor shaft and another is attached to the drive shaft, and the two sprockets are linked with a bicycle chain.

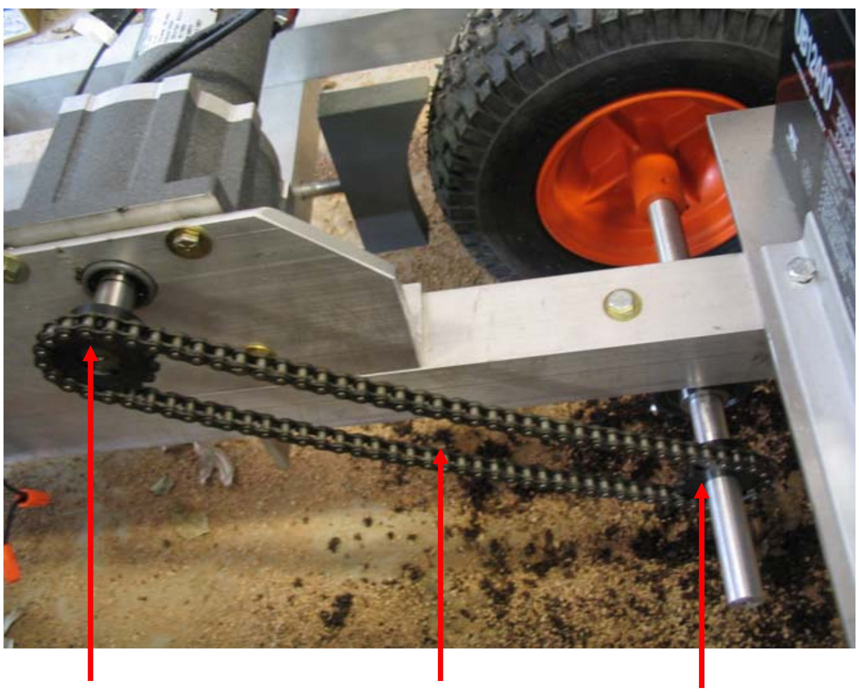


Figure 17. Chain and sprocket drive.

Mechanical Brake

The brake consists of a plunger, rod, and crescent-shaped piece of PVC. The plunger itself is a toggle clamp used for industrial manufacturing. We cut a piece of ½-inch aluminum rod and a section of 1-inch thick PVC. To connect all three parts together, the rod needed to be threaded for a length of 1.75 inches on either end so that it could fit into the plunger (black portion) and the PVC. A hole slightly smaller that ½-inch diameter needed to be tapped into the PVC so that the rod could be tightly fitted into it. It was important that the rod not slip if it should be engaged while pressed onto the tire.

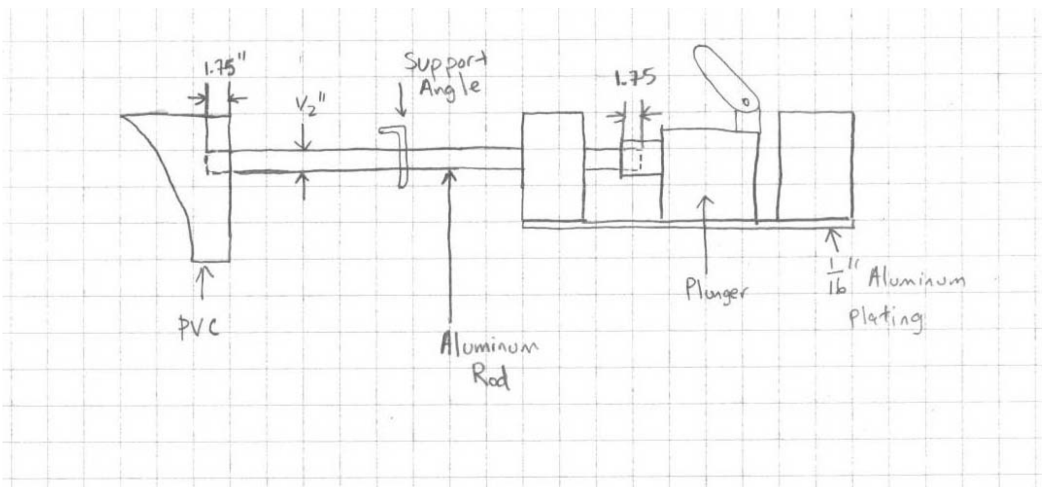


Figure 18. Side view sketch of emergency brake.

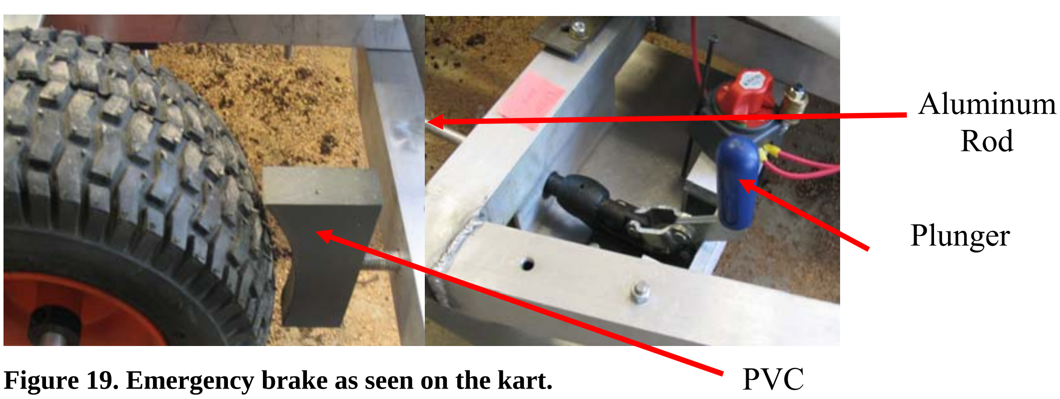


Figure 19. Emergency brake as seen on the kart.

System Design

General

Our basic design for the system is a simple analog input from a joystick, which is processed by a microcontroller, then sent to the motor controllers, where it is then relayed to the motors to produce wheel rotation. We wanted to build a closed-loop system in which sensors would read the tire speed and provide feedback into the control loop to adjust the outputs accordingly. Though we were not able to characterize the system to properly design a control feedback loop, the motor controllers we selected do provide a closed-loop feedback system to compensate for loading. The control system that we ended up using on our kart is shown in the figure below.

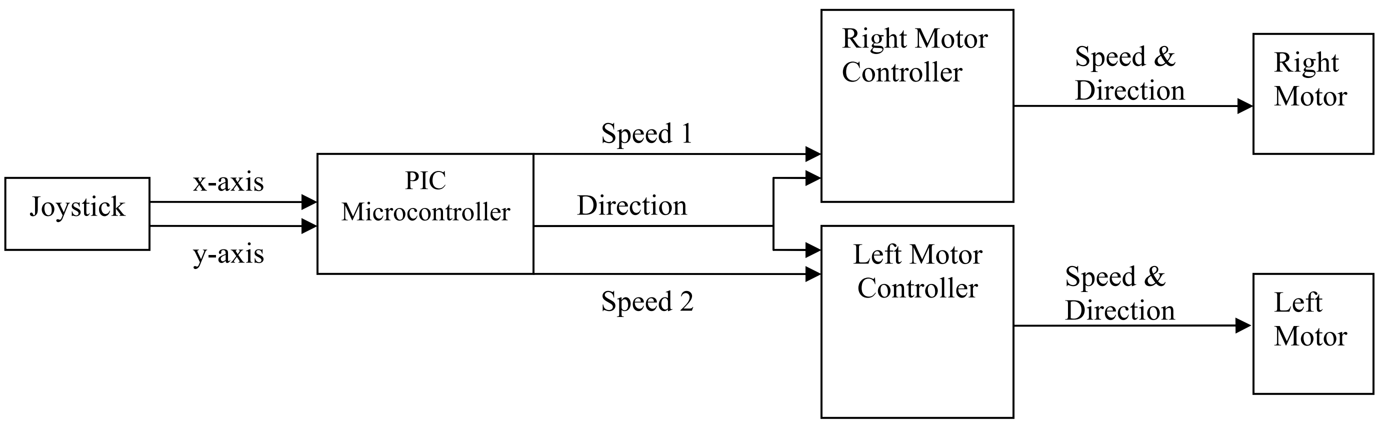


Figure 20. Control system design for drive-by-wire vehicle.

Analog and digital signals are used throughout the system. Some devices can receive and output both types of signals, while others used in the system can only receive or output one type of signal. Since we are using only the x- and y-axis outputs, the joystick is outputting two analog signals for each axis to the PIC microcontroller. The PIC can receive and output both digital and analog signals. The motor controllers can only take in an analog speed input and a digital direction input, and they only output digital signals to the motors.

We use Pulse Width Modulation (PWM) to control the speed of the motors. The reason we use PWM is because of power efficiency and simplicity of control. Pulse Width Modulation involves switching the power on and off at a high frequency. Power is conserved because it is being cycled on and off at a chosen frequency rather than being kept on all the time. PWM signals are easy to control because one only needs to change the amount of time the power is on, this is known as controlling the duty cycle. PWM signals like the one used to operate the vehicle are illustrated below.

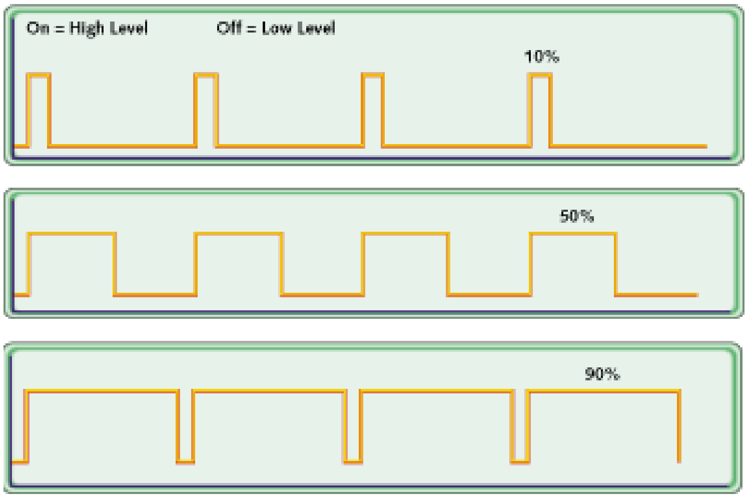


Figure 21. Three different PWM signals, same frequency, different duty cycles.
Source: http://www.netrino.com/Publications/Glossary/PWM.html, March 2006.

The images show three different PWM signals with the same period (i.e. the same frequency). When the PWM signal reads high (5V), this indicates that the power is on, and when the signal reads low (0V), this indicates the power is off. A PWM signal is characterized by its duty cycle. The duty cycle of the PWM signal refers to the percentage of time the power is on (5V).

$$Duty\ Cycle = \frac{t_{on}}{T}$$

t_{on} = Amount of time signal is high (5V) in seconds
T = Period of signal in seconds

The first signal has a 10% duty cycle, the second 50%, and the third 90%. The higher the percent duty cycle is, the greater the average dc voltage value. The average dc voltage is calculated by multiplying the duty cycle and 5 volts. For the first signal the average dc voltage is 0.5V. To get the average dc voltage for the other two signals you would repeat this procedure. It is concluded that the signal with the greater percentage duty cycle has the greater average voltage. An increase in the average dc voltage results in more voltage being supplied to the motors, resulting in the motors turning faster. Beginning with the driver input, we will describe how the speed and direction signals are initiated, processed, and translated into tire rotation.

Joystick

Building this system required that we first deal with how we were going to feed in the driver speed and direction input. Going with the “drive-by-wire” design and the desire to make a “sleek” input device, we decided to use a joystick with x- and y- axis outputs. The advantages of using a joystick are that it does not require a range of motion like the conventional steering wheel, and it can also be placed according to the driver’s preference, either in the driver’s lap or to the left or right side of the driver. Power is supplied to the joystick from the positive 5V of the PIC board and it is grounded PIC’s ground, which is subsequently grounded to the frame of the kart. The joystick’s position along the x- and y- axis are defined by two potentiometers, one for each axis, the position being proportional to the voltage output from each axis. When the joystick movement is restricted to the y-axis, the output of the y-axis potentiometer ranges from 0V to 5V: 0V indicating that the joystick is pushed all the way forward, and 5V indicating that the joystick is pulled all the way backwards. When the joystick is in the center position, the y-axis potentiometer should ideally read 2.5V. The x-axis potentiometer works in a similar fashion; its output ranges approximately from 0 to 5V, and 2.5V indicates the ideal center position. The figure and the tables below illustrate the output of the x- and y-axes of the joystick.

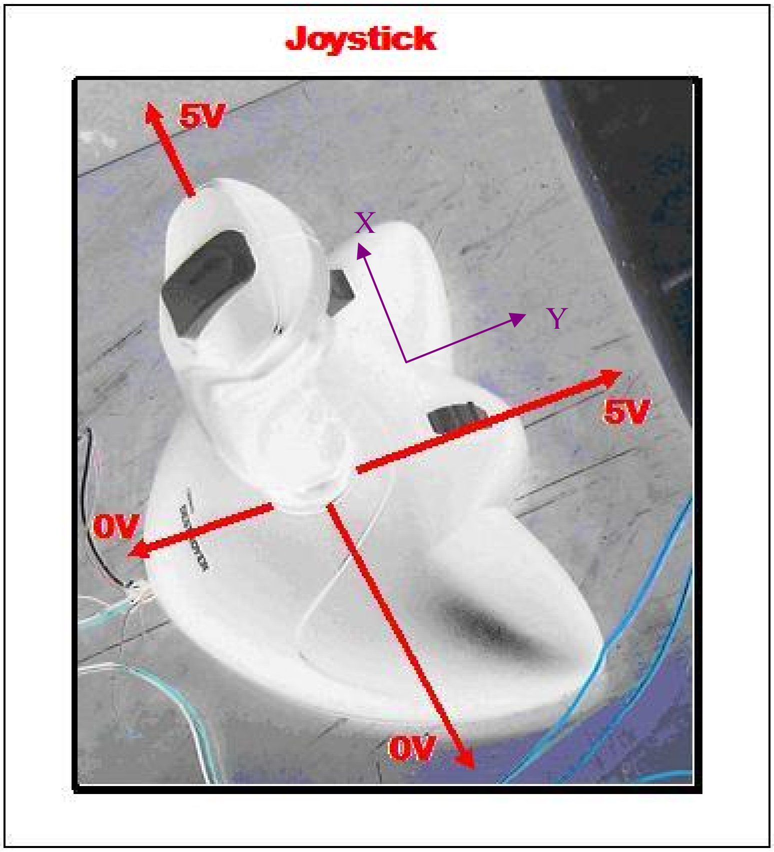


Figure 22. This image displays the limits of the joystick outputs according to its physical position.

Table 8. Joystick outputs according to x-coordinate.

Joystick Position along X-Axis (Green Wire)	**Voltage Output** (V)
Center	1.99
Full Left	0.05
Full Right	4.65

Table 9. Joystick outputs according to y-coordinate.

Joystick Position along Y-Axis (Gray Wire)	**Voltage Output** (V)
Center	2.23
Full Forward	0.05
Full Backward (Reverse)	4.97

From the tables above, one can see that full forward, reverse, left, and right voltage values do not exactly equal their ideal voltage value, but they are close enough for the operation of the vehicle. The only problem we encountered with this discrepancy between actual and ideal voltage-position values was defining the center (i.e. the neutral position). We will discuss later on how we resolved this discrepancy. The next step was to process these analog voltage inputs with an algorithm that would then translate it to an analog voltage to dictate the speed and digital output to dictate direction.

As the joystick is pushed away from the neutral position (center) the duty cycle is expected to increase as well as the motor speed. The voltage reading from each axis indicates the direction and the speed at which the driver would like to have the kart travel. In the case of direction, if the driver desires to move the kart in the forward direction, the joystick is moved towards the front, and the voltage value should be between 0 and 2.5V. If the driver wants to move the kart in reverse, the joystick is moved towards the driver, and the voltage value should read between 2.5V and 5V. If the driver intends to move left or right, the joystick should be moved in the intended direction and the voltages should read between 0V and 2.5V, and between 2.5V and 5V, respectively. In the case of speed, the greater the absolute difference between the current y-axis position and the central position of 2.5V, the greater the speed of the kart in the indicated direction. For example, if the previous y-axis voltage reading is 4V and the current y-axis reading is 3V, this tells us that the driver has slowed down the speed of the kart because there was originally a 1.5 voltage difference and currently there is only a 0.5V difference. To translate the analog outputs of the joystick into the appropriate direction and speed signals recognized by the motor controllers, the analog signals must be sent to the microcontroller in order to be processed into the type of signals the motor controller can accept.

Joystick to Microcontroller

The general idea is that the microcontroller reads the x- and y-axis voltages from the board's ports and outputs appropriate speed and direction information via another port to the motor controllers. The algorithm for processing the joystick inputs into appropriate outputs is explained in more detail in the section describing the PIC Code. The x-y axis potentiometers of the joystick are connected to the PIC board via pins E0 and E1, respectively located in port E. Leaving out the full details of the code, the PIC16F877 chip is given the command to read in from both pins. The analog voltages read in from the input pins are converted to an equivalent 8-bit binary value that ranges from 0 to 255. This means that we have 0.02V resolution for the input (i.e. every 1-bit change in binary value represents 0.02V change in the analog voltage input). For example, if the analog input is 0V, 2.5V, or 5V, then the binary equivalent read by the microcontroller would be 0, 127, or 255 respectively and a change from 127 to 128 indicates a voltage change from 2.50V to 2.52V respectively.

As we discussed earlier, there was a problem determining the analog x and y values of the joystick's neutral position, but this was mitigated by defining a "deadband" region centered around the neutral position (the limits of the "deadband" region are defined in the PIC C code). We consider this region a "deadband," because this is where we invoke the stop command. Since the center of the y-axis is 2.23V, the binary equivalent is approximately 112. The x-axis center is 1.99V, so the binary equivalent is approximately 100. The binary value of the central x- and y- axis positions was also determined through a more direct method of displaying the most significant four bits of the 8-bit value using the four LEDs on the PIC board. With this method, we approximated the x- and y- centers at about 102 and 116, respectively. In debugging, it was very helpful to use the LEDs to confirm that the joystick position was read into the PIC properly.

By relating a y-axis or x-axis reading to this central value, we can calculate the speed of the kart. If the y-axis reading is above 112, then the intended direction of the kart is forward, and if the reading is below 112, then the intended direction is reverse. As the absolute difference between the y-axis reading and 112 increases, then the kart speed should increase linearly. To find the x-direction of the kart, we similarly calculate if the x-axis reading is above or below the x-axis center. The greater the absolute difference between the x-axis reading and x-axis center, the sharper the turning of the kart is in the intended direction. By using the value of the actual axes' centers instead of the theoretical center values of 2.5V (127), we effectively adjust the center to be where the joystick indicates rather than where we theoretically calculate it to be. After the microcontroller converts the analog signals to their binary equivalents, the appropriate duty cycle is calculated. This is discussed in more detail when we describe the PIC C code.

Microcontroller to Motor Controller

The PIC16F877 outputs a PWM signal with the appropriate duty cycle via pins RC1 and RC2 located on port C on the PIC board. Since we are controlling two motors independently to create a turning differential, we compute two different PWM signals (one for the left wheel and one for the right wheel) with different duty cycles and output them through pins RC1 and RC2. Each of the PWM outputs of RC1 and RC2 must be fed through a first-order RC filter, because the motor controllers can only receive an analog voltage signal for its speed input. The schematic for the RC filter is shown below.

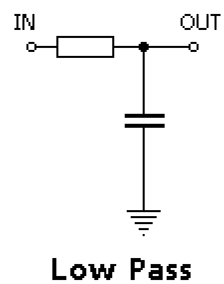


Figure 23. First order RC filter.

Source: http://www.netrino.com/Publications/Glossary/PWM.html, March 2006.

The RC filter takes the PWM as an input and smoothes it out into a steady dc voltage. The average dc voltage of the PWM is the steady voltage that should be read between capacitor and ground. There are a total of two RC filters, one for each PWM output. The resistance is 7.5 kΩ and capacitance is 0.01 μF, and these values are identical for each filter. The resistance and capacitor values were chosen based on the frequency of the PWM output signals. Each time the PWM signal is high, the capacitor charges up, increasing the output voltage. When the PWM signal is low, the capacitor begins to discharge, causing the output voltage to decrease. Since both PWM signals coming out of the RC pins have a 1kHz frequency, the time constant of the RC filter needs to be considerably lower than 1kHz so that the output voltage will not decrease too much before increasing again. The resistance and capacitance values should not be so great that the output voltage is slow to respond to changes in the filter input. The steady dc voltage is then fed to the motor controller potentiometer, which will control the speed of motors.

In addition to the speed, the PIC must also output a digital signal to the motor controllers so that the motors will rotate forward, rotate reverse, or stop. The motor controller has a set of four switches indicating four different operational modes: 1) Run Forward (green wire); 2) Stop Forward (blue wire); 3) Run Reverse (yellow wire); 4) Stop Reverse (brown wire). If the motor controller is to be in one of these modes, then the switch corresponding to that particular mode must be grounded (logic 0), the equivalent of turning on the switch, and if it is to exit that mode, then the pin must be made a float (logic high-impedance), the equivalent of turning off the switch. The program code loaded onto the PIC processes the x-y inputs of the joystick and determines if the motors must rotate in the forward, reverse directions or if the motors should be stopped. The PIC outputs to Port D through pins RD4, RD5, RD6, and RD7, which are wired to the Run Forward, Stop Forward, Run Reverse, and Stop Reverse switches, respectively, on both motor controllers.

The motor controllers also have jumpers that can be set to modify how it switches between these four modes. The motor controller datasheet and manual are included in Appendix D. For our project, we decided to set the jumpers so that the driver could easily switch between going in the forward and reverse directions as well as continuing in the same direction after a moment of stopping. A possible jumper setup is included in the figure below.

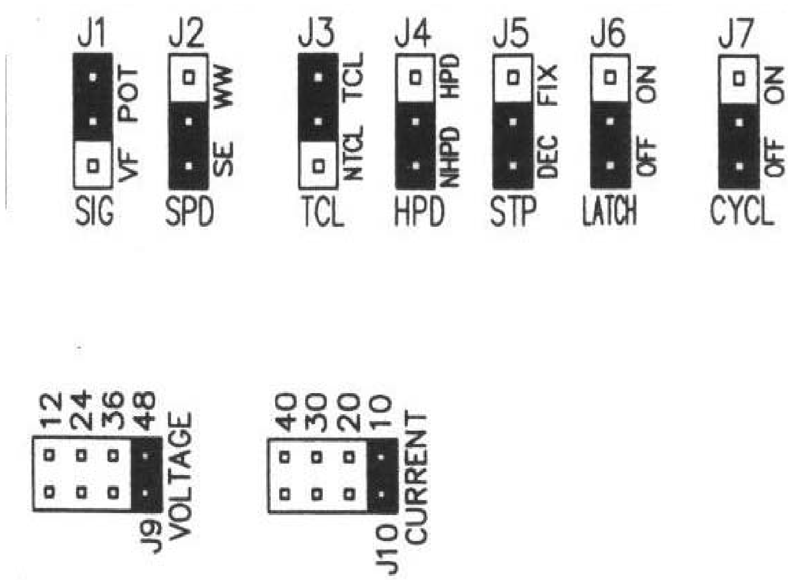


Figure 24. Jumper configuration for each motor controller.

J1 is set to POT so that the speed can be controlled by the average dc voltage value from the RC filter. J4 is set to NHPD (No High Pedal Disable) so that the speed input from the RC filter does not have to be set to zero before the motor is allowed to run. J7 is should be set to OFF because we are not using dynamic braking. J8 is set to NO, which turns off the option of having a fault relay output condition. J9 is set for 24V because it is the operating voltage of each motor.

J2 is set to SE (the Single-Ended directional setting) which has the Run Forward/Run Reverse switches determine which direction the motor is turning and the full range of potentiometer (0-5V) to determine the speed in the selected direction. J6 is set to the OFF position, because we want to be in maintained switching mode. In this mode, the switches for Stop Forward and Stop Reverse function as limit switches, so when used, they override the deceleration feature by shorting the motor leads. The rate of deceleration is set with J5 – Decel, which allows us to adjust the deceleration trimpot to set the deceleration time (this pulsates the motor leads to allow for a controlled stop up to 15s in duration).

J3 is set to TCL (Timed Current Limit) so that the motor controller shuts down if the current exceeds the set current limit for more than 7 seconds. The current limit is set by a combination of another jumper, J10, and the current limit trimpot. For the operation of the kart, each motor controller was set to have a current limit of 60A by setting J10 to 30A and the current limit trimpot to 200% of the J10 value.

Motor Controller to Motors

Transmitting the output of each motor controller to its corresponding motor is straightforward. The set of positive and negative terminals on a motor controller are wired to the positive and negative wires, respectively, on its corresponding motor. The connection between the left motor controller and the left motor follow this conventional wiring; however, the connection between the right motor controller and the right motor were swapped (i.e. the negative output terminal of the motor controller was connected to the positive wire of the right motor, and the positive output terminal of the motor controller was connected to the negative wire of the right motor). This swapping was necessary, because the left and right motors face each other on the kart and they receive the same directional signal (Run Forward or Run Reverse), but their rotation must be opposite of each other in order to get the tires to spin in the same linear direction (forward or reverse).

PIC Code

The PIC micro-controller was programmed using C code. The full PIC C code can be found in Appendix F. The code was devised to accomplish three concrete tasks: (1) read in the x- and y- coordinate positions of the joystick, (2) output float and ground signals to set the direction switches on the motor controller, and (3) output PWM signals to adjust the speed on the motor controller. A simple algorithm was created to process the x- and y- coordinates of the joystick and output the appropriate direction and speed commands. The outer statements check if we want to turn left, turn right, or not turn based on the x-axis input. The first inner statements check if we want to go forward or go reverse based on the y-axis input, and the inner-most statements determine the speed setting for each motor based on the x- and y- axis inputs. Separate functions were created to execute stop, run forward, and run reverse.

The speed is set by setting the duty cycle. The duty cycle is set with 10 bits, so it ranges from 0 to 1023. The joystick position goes from 0 to 5V, but it is processed by the PIC with 8 bits, so it ranges from 0 to 255. It was determined experimentally (using the PIC LEDs to display the four most significant bits) that the x- and y-axes are centered at approximately 102 and 116, respectively. In the code, we created a "deadband" region described previously. In this region, each motor is set to stop; the speed of each motor is also set to zero to insure that the vehicle stops moving when the system is first powered on or the stop command is delayed, missed, or, for any reason, not relayed.

Both motors are assigned the same speed to go straight in forward or reverse (no turning). The speed is calculated according to the joystick's y-axis input *yduty* and is set as follows:

```
IF ( y < (YCENTER - 12) ){
THEN yduty = (1 - (y/(YCENTER))) * 1023.0;

IF ( y > (YCENTER + 32)
THEN yduty = (1 - ((255 - y)/(255 - YCENTER))) * 1023.0;
```

xduty is set similarly.

Turning is achieved by setting one motor slower than the other (no mechanical differential required). The faster wheel is assigned the speed *yduty* and the slower wheel gets *yduty* scaled by *xduty* as follows: yduty - ((xduty/1023)*yduty).

System Integration

Electrical Connections

The final network wiring of all the electrical components is fitted with specific gauge wires to accommodate the amount of current being carried from component to component. We used the American Wire Gauge Table of Standards (Appendix G) to find the appropriate wire gauge between each component. The wiring diagram below illustrates how the electronics is powered. Grounding refers to connecting devices to the frame of the kart. We mentioned earlier that the PIC board is powered by a 9V battery.

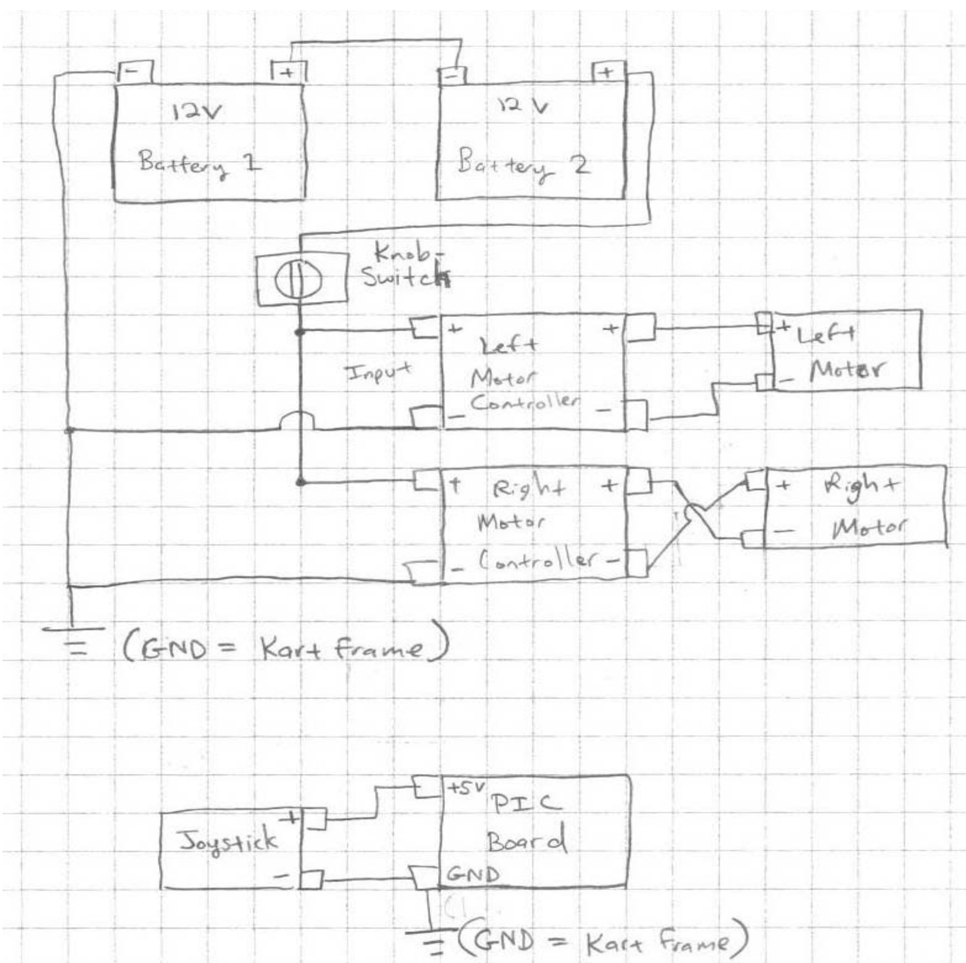


Figure 25. Wiring diagram showing how each device is powered.

Initially, we made electrical connections using 24-gauge solid wire without considering the fact that we were supplying a great amount of current to the motor controllers and motors. Thus, we experienced smoking wires when testing out the kart with a load (because this required more current than testing the unloaded motors).

The first major modification of our wiring was switching from solid to stranded wire. Solid wire, although flexible to a degree, can easily break after a few flexures or extreme bending. The stranded wire can withstand more bending which is ideal because we often loop the wire around parts of the frame in order to prevent it from interfering with the motor and tires. In addition to switching the type of wire being used, we also needed to choose the appropriate gauge to withstand the amount of power being supplied between each device. Since the motor controllers each require 24V, the two 12-V batteries were connected in series to provide 24V. The connections between the batteries and the motor controllers were replaced with 10-gauge stranded wire to carry 24 volts and a maximum of 80amps.

The connections between the individual motor controllers and their respective motors were replaced to match the 16-gauge wires that came with the motors. The smaller connections on the PIC board and motor controllers were replaced with 24-gauge stranded wires. The connections between the joystick, PIC board, and motor controllers only required 24-gauge wire because there is considerably less current being carried between each component; therefore, outfitting these connections with a lower gauge (greater diameter) wire would have caused the network connections to be unnecessarily bulky and less cost-effective.

We also experienced problems with shorting out wires on the motor controller, specifically the battery terminals which were placed extremely close together – a poor design decision by the manufacturer. To solve this problem, we used insulated lugs that were crimped to the 10-gauge wires coming from the batteries so the batteries could have a firm connection to the input terminals of the motor controllers. Lugs were also used for the output terminals of the motor controllers; these were outfitted for 16-gauge wires as we described for the motors in the previous paragraph. We used screw clamps to connect wires to the terminals of the batteries in order to prevent accidental disconnection of wires.

A terminal strip was used to relay connections between the joystick and PIC board and between the PIC board and motor controllers. This made for cleaner connections between devices and helped us to avoid shorting wires together.

Mounting Electronics

We placed both motor controllers into individual Gladware containers which are used for weatherproofing and protecting the electronics from ground debris. These Gladware containers fit snuggly into the triangular pocket created by the frame members and plating on the left hand side of the kart. The PIC board is laid on top of the Gladware containers.

Performance

Testing and Results

We planned several tests to evaluate the performance of the vehicle and the achievement of design specifications. Some tests are qualitative, while others offer quantitative results. A review of the performance evaluations we planned to conduct and the results that were obtained are discussed as follows:

- Test outdoor use driving along college pathways: design goal required user to be able to steer, maintain, and adjust speed as necessary
- Test vehicle operation with larger driver: design goal set kart to function with a maximum driver load of 250lbs
- Test avg/max speed: revised design goal set to 4/12mph
- Test rate of acceleration: design goal set to $1 ft/s^2$
- Test hill-climbing ability: design goal set to 16-20% grade
- Test range along flat terrain: design goal set at 1-2hr

A bike computer was attached to the kart to serve as a quick way of the kart determining and displaying the kart speed during operation. The bike computer works by having a sensor mounted on the battery plate where it is close enough to sense a magnet that is taped onto the side of the tire. The difficulty with this speed sensing setup is that the magnet can fall off once the adhesiveness of the tape wears out, and the bike sensor has to be fairly close to the tire to detect the magnet attached to the rotating tire. Because of this difficulty and complications experienced when using the first bike computer we acquired, we were not able to employ it in the data acquisition process. We have since then obtained a better bike computer that we may use in the following weeks.

The first test qualitatively assessed the function of the vehicle. Our general evaluation concludes that the vehicle is operable along college pathways, but the ability to steer and maintain or adjust speed as necessary depends on the user's experience or skill with using the joystick. We specifically address four areas of interest or concern relating to the vehicle's operation: joystick handling, castor behavior, system response, and radial turning.

We found that using a joystick to operate the vehicle depends on how the joystick handles, by which we mean its sensitivity, range, and resistance to motion. For this, a more robust steer-by-wire system could be of use to provide feedback from the road to the feel of the joystick. It was also determined that the behavior of the castor can cause a significant and inconvenient delay in directing the vehicle. This problem occurs primarily when changing direction (forward or backward) and is exacerbated in confined spaces. The system response was thought to be sufficient for the vehicle's application; however, a small delay can occur between the input command to go forward (pushing the joystick forward) and the response of the motor controllers. What we observed was one controller responding faster than the other, so one wheel begins moving before the other, and the vehicle will turn slightly before moving forward. This problem can be easily avoided if the user simply adjusts the joystick forward slowly, allowing both controllers to respond before accelerating. Finally, since the drive wheels operate independently – regulated by separate motor controllers – it is possible that the vehicle can turn with a zero degree radius if one wheel rotates forward and the other rotates backward. We chose to simplify the system by using one standard microcontroller board. This limited the number of outputs we could set, so the drive wheels currently can only rotate in the same direction, which allows radial (but not zero degree) turning. With a second microcontroller or a board with additional ports (outputs), zero degree turning could easily be achieved.

A brief test operation conducted by Professor Erik Cheever leads us to believe that the vehicle could successfully accommodate a 250 lb driver in its general operation, but, specific performance criteria such as speed and acceleration have not been tested under maximum loading. They were tested with smaller loads in the range of 100 - 150 lbs. Conducting several time trials by measuring the vehicle's time to traverse a set distance at top speed, we determined that the vehicle's top speed averaged about 7.2 mph. It is important to note that the motor controller's load compensation feature had not been calibrated to the load (due to limited means of data acquisition at the time), so we believe the vehicle's top speed will in fact be greater. We intend to test this in the coming week.

We also performed several time trials to assess the vehicle's rate of acceleration – the time to accelerate from rest to top speed – along flat terrain. Again, due to limited means of data acquisition, top speed was determined qualitatively by the driver. We found that the acceleration equaled 3.7 ft/s^2 with the compensation still uncalibrated to the load and the "accel" trimpot facing 9 o'clock – not the left-most limit, which is around 7 o'clock. We believe that there would be a higher rate of acceleration if the load compensation were calibrated and the acceleration trimpot was adjusted to its maximum (7 o'clock) setting.

Finally, we tested the vehicle's hill climbing ability by trying to drive it up the hill behind McCabe library and Willets dormitory (16-20% grade). The vehicle successfully climbed the lower portion of the hill, accelerating from rest to a low speed, but remained stopped at the steeper portion – just breaking even, so to speak. It is our intent to try this hill again after the load compensation is properly calibrated. We did find that the vehicle could easily navigate other hills on campus, which have a lower grade (estimated between 4 and 8% grade).

We also wished to evaluate the system's range, that is, for what duration of time and for what measure of distance can the vehicle operate along flat terrain? Due to time constraints and factors that delayed vehicle testing, we were unable to get a genuine measure of the system range. Based on the accumulated duration of testing done, we conjecture that the range will be at least 1 hour. We conclude from these results that the vehicle design satisfactorily fulfills the original (or where revised) design specifications.

Future Work

For future work, we anticipate students from succeeding classes to take over this project after we graduate. It would be expected that some vehicle alterations and improvements may be made. We believe it may be of interest to consider replacing or redesigning the front castor wheel to relieve the delay issue in the vehicle's performance. The addition of an impact bumper would also be useful to help protect the structural integrity of the chassis and whatever may be at the other end of a collision (which may occur, especially with a new user). It would also be useful to improve the way in which the magnet for the bike computer is connected to the wheel or tire (tape is not a sufficient long-term solution). Other features, such as a dampening system for the tires, permanent compartments for the electronics, or a shell for the chassis, are improvements that could be made to the vehicle.

We think it would be of considerable interest to enhance the wire connections linking the electronics (joystick, microcontroller, and motor controllers). The soldered connections are only sufficient if the electronics are stabilized on the vehicle; currently, the PIC microcontroller is not fully secured, and we experienced a connection failures as a result. Furthermore, the terminal strip used is tedious and less than ideal. We believe it would be advantageous to acquire a terminal strip that has more sophisticated connections than screws, like those used in stereo systems, that would allow the user to quickly and easily disconnect one electronic component or another. For example, this modification would allow the user to remove the microcontroller from the system more quickly and easily, so that it may be brought to the laboratory to update the code.

It would also be useful to acquire a permanent bike computer, not only for data acquisition, but for feedback to the driver. We also foresee students adding sensors and implementing more complex control systems. In addition, it may be of interest to augment the system with the installation of regenerative braking. It might even be possible, with appropriate funding, to replace the lead acid batteries with a hydrogen fuel cell. Finally, further testing to evaluate the system's power, torque, efficiency, etc. could be useful.

Acknowledgements

We would like to thank our advisors, Professor Erik Cheever and Professor Carr Everbach, for their wisdom and guidance. We would also like to extend a warm thanks to machinist Grant "Smitty" Smith for all his patience, support, and assistance. We also must thank Ed Jaoudi and Holly Castleman for their continuous help and patience. Mike Boyd with Facilities Management was crucial in obtaining topographic campus maps and wheel and tire information. And finally, we would be negligent if we also did not thank our friends and family for all their support.

Appendices

Appendix A

Images depicting go-kart roll bar design.

Appendix B

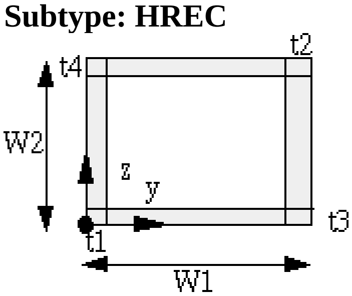
ANSYS

Model Settings

```
***** UNITS *****
 BRITISH INCH UNITS SPECIFIED FOR INTERNAL
  LENGTH      = INCHES(IN)
  MASS        = LBF-S**2/IN
  TIME        = SECONDS(SEC)
  TEMPERATURE = FAHRENHEIT
  TOFFSET     = 460.0
  FORCE       = LBF
  HEAT        = BTU
  PRESSURE    = PSI (LBF/IN**2)
  ENERGY      = IN-LBF
  POWER       = IN-LBF/SEC
```

```
***** CROSS-SECTION *****
```

Subtype: HREC



Data to be supplied in the value fields:
W1, W2, t1, t2, t3,t4
W1=Outer width of the box
W2=Outer height of the box
t1,t2,t3,t4=Wall thicknesses

SECDATA, *VAL1, VAL2, VAL3, VAL4,...,VAL10*

```
***** COMMANDS USED *****
```

Element Type for members of rectangular tubing set…
GUI:
Preprocessor -> Element Type -> Add/Edit/Delete: BEAM 188
Command Line:

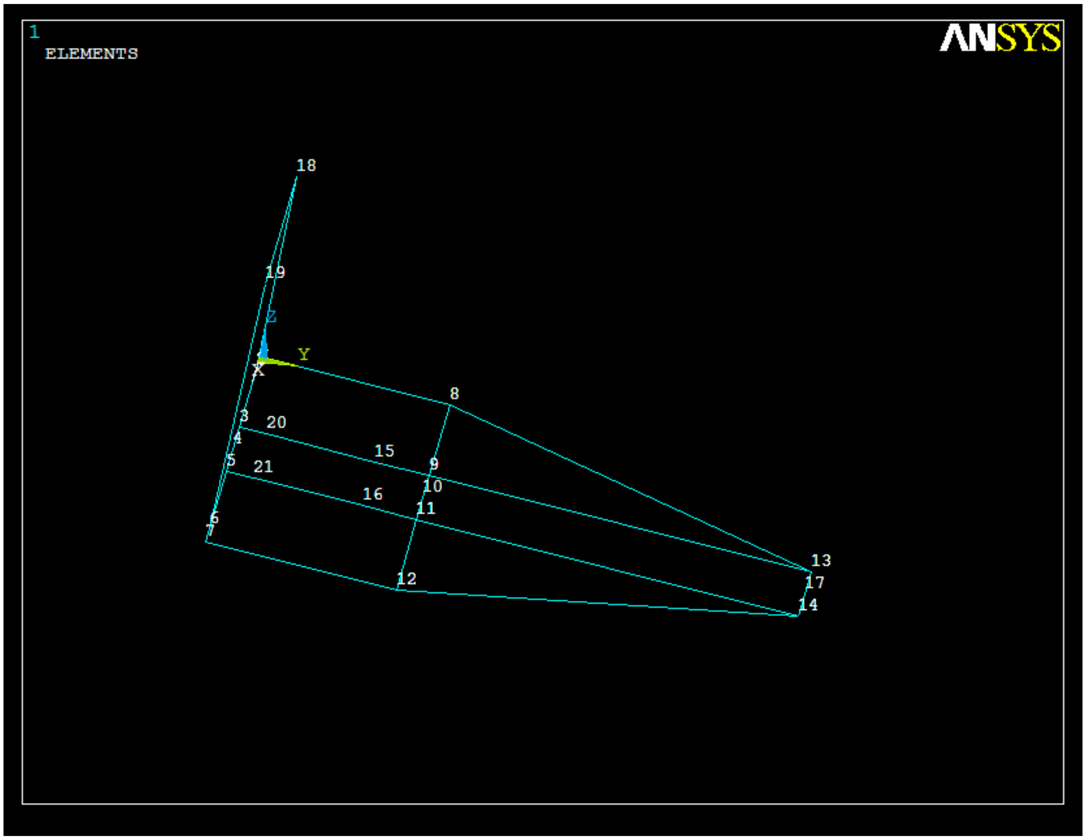
SECTYPE, 188 , BEAM, HREC, S2x2x1875
SECDATA, 2, 2, 0.1875, 0.1875, 0.1875, 0.1875
SECNUM, 188

Material Properties for members of Aluminum T6061 set…
GUI:
Preprocessor -> Material Props -> Structural –> Linear -> Elastic -> Isotropic

Modulus of Elasticity (E) = 10E6

Poisson’s Ration (v) = 0.33

***** GRAPHICAL ELEMENT MODEL *****



***** LIST OF NODES DEFINED *****

LIST ALL SELECTED NODES.   DSYS=   0

NODE	X	Y	Z	THXY	THYZ	THZX
1	0.0000	0.0000	0.0000	0.00	0.00	0.00
2	3.0000	0.0000	0.0000	0.00	0.00	0.00
3	16.000	0.0000	0.0000	0.00	0.00	0.00
4	21.000	0.0000	0.0000	0.00	0.00	0.00
5	26.000	0.0000	0.0000	0.00	0.00	0.00
6	39.000	0.0000	0.0000	0.00	0.00	0.00
7	42.000	0.0000	0.0000	0.00	0.00	0.00
8	0.0000	28.000	0.0000	0.00	0.00	0.00
9	16.000	28.000	0.0000	0.00	0.00	0.00
10	21.000	28.000	0.0000	0.00	0.00	0.00
11	26.000	28.000	0.0000	0.00	0.00	0.00
12	42.000	28.000	0.0000	0.00	0.00	0.00
13	16.000	84.000	0.0000	0.00	0.00	0.00
14	26.000	84.000	0.0000	0.00	0.00	0.00
15	16.000	20.000	0.0000	0.00	0.00	0.00
16	26.000	20.000	0.0000	0.00	0.00	0.00
17	21.000	84.000	0.0000	0.00	0.00	0.00
18	9.0000	0.0000	42.000	0.00	0.00	0.00
19	33.000	0.0000	42.000	0.00	0.00	0.00
20	16.000	4.0000	0.0000	0.00	0.00	0.00

NODE	X	Y	Z	THXY	THYZ	THZX
21	26.000	4.0000	0.0000	0.00	0.00	0.00

```
***** LIST OF NODAL FORCES DEFINED *****

LIST NODAL FORCES FOR SELECTED NODES        1 TO      21 BY       1
 CURRENTLY SELECTED NODAL LOAD SET= FX   FY   FZ   MX   MY   MZ

    NODE  LABEL     REAL           IMAG
       1  FZ     -15.0000000      0.00000000    (drive wheel)
       7  FZ     -15.0000000      0.00000000    .
       9  FZ     -62.5000000      0.00000000    (fraction of 250lb driver)
      11  FZ     -62.5000000      0.00000000    .
      15  FZ     -62.5000000      0.00000000    .
      16  FZ     -62.5000000      0.00000000    .
      20  FZ     -33.0000000      0.00000000    (battery)
      21  FZ     -33.0000000      0.00000000    .

***** LIST OF CONSTRAINTS DEFINED *****

 LIST CONSTRAINTS FOR SELECTED NODES        1 TO      21 BY       1
 CURRENTLY SELECTED DOF SET= UX   UY   UZ   ROTX ROTY ROTZ

     NODE  LABEL     REAL           IMAG
        1  UX     0.00000000      0.00000000    (drive wheel)
        1  UY     0.00000000      0.00000000
        1  UZ     0.00000000      0.00000000
        1  ROTX   0.00000000      0.00000000
        1  ROTY   0.00000000      0.00000000
        1  ROTZ   0.00000000      0.00000000
        7  UX     0.00000000      0.00000000    (drive wheel)
        7  UY     0.00000000      0.00000000
        7  UZ     0.00000000      0.00000000
        7  ROTX   0.00000000      0.00000000
        7  ROTY   0.00000000      0.00000000
        7  ROTZ   0.00000000      0.00000000
       17  UX     0.00000000      0.00000000    (castor wheel)
       17  UY     0.00000000      0.00000000
       17  UZ     0.00000000      0.00000000
       17  ROTX   0.00000000      0.00000000
       17  ROTY   0.00000000      0.00000000
       17  ROTZ   0.00000000      0.00000000
```

Appendix C

Link to motor web page and data sheet.

Groschopp

Web page: http://www.groschopp.com/products/index.php?act=details&num=56267

Appendix D

Link to motor controller datasheet and manual.

KBElectronics

Datasheet:
http://www.kbelectronics.com/kbsearch/s_list.php?from=2&col_1=2&col_2=13&col_3=&col_4=&col_5=&col_6=&col_7=&res=2#

Manual:
http://www.kbelectronics.com/catalog_chassis.htm

Appendix E

Choices for kart tires (hard copy only).

Appendix F

PIC C Code

```
#include "\\Data-software\classes\Natural Sciences +
Engineering\Engineering\Transfer\0DEE90\PIC\HEX2_Wholesystem_trial1.h"
// Forward is set with Run Reverse and Backward is set with Run Forward due to how the wires
are set from the controller to the motors. (check)


#fuses HS,NOWDT,NOPROTECT,NOLVP
#use delay(clock=10000000)
#use rs232(baud=9600, xmit=PIN_C6, rcv=PIN_C7, BRGH1OK)

#define YCENTER 116.0
#define XCENTER 102.0


// global variables
long duty1;
long duty2;
// functions
void stop();
void RF();
void RR();

void main() {

  float x; // input from joystick
  float y; // input from joystick
  float button; // input from joystick - read button
  float setduty1;
  float setduty2;
  float xduty;
  float yduty;

  int LEDy;
  int LEDx;
  int LEDbutton;

  setup_ccp1(CCP_PWM);    // Configure CCP1 as a PWM
  setup_ccp2(CCP_PWM);    // Configure CCP2 as a PWM

  setup_timer_2(T2_DIV_BY_4, 255, 1); // Set up timer2 for PWM
```

```
  // JOYSTICK INPUT SETUP
  setup_adc_ports(NO_ANALOGS);
  setup_adc(ADC_OFF);
  setup_adc(ADC_CLOCK_DIV_32);
  setup_adc_ports(ALL_ANALOG);

  SET_TRIS_D(0x0F); // RD4-RD7 are outputs
  SET_TRIS_E(0x03); // RE0 and RE1 are inputs

  // set all switches to float
  output_float(pin_D4);   //RF
  output_float(pin_D5);   //SF
  output_float(pin_D6);   //RR
  output_float(pin_D7);   //SR

  // initiate to stop for operation
  //output_low(pin_D7); // ground stop reverse
  //output_low(pin_D5); // ground stop forward

  // Main loop
  while (1) {

    set_adc_channel(5); // channel AN5 (RE0) will be used for the next read_adc() call.
    delay_ms(10);
    y = read_adc(); // read voltage from RE0, input from joystick
    delay_ms(10);
    LEDy = y;

    set_adc_channel(6); // channel AN6 (RE1) will be used for the next read_adc() call.
    delay_ms(10);
    x = read_adc(); // read voltage from RE1, input from joystick
    delay_ms(10);
    LEDx = x;

    output_b(LEDy>>4);

/*
y< -- setduty1 = (1 - (y/(YCENTER))) * 1023.0;
y> -- setduty1 = (1 - ((255 - y)/(255 - YCENTER))) * 1023.0;
x< --  setduty2 = (1 - (x/XCENTER)) * 1023.0;
x> --  setduty2 = (1 - ((255 - x)/(255 - XCENTER))) * 1023.0;
*/
```

```
// TURN RIGHT - set duty1/left faster than duty2/right
if (x < (XCENTER - 16) ) {
    // set xduty
      xduty = (1 - (x/XCENTER)) * 1023.0;

    // set direction and speed
    // GO FORWARD
    if ( y > (YCENTER + 32) ){
      // RF code
      RF();
      yduty = (1 - ((255 - y)/(255 - YCENTER))) * 1023.0;

      duty2 = yduty;
      duty1 = yduty - ((xduty/1023) * yduty);

      // set pwm duty
      set_pwm1_duty(duty1); // RC2=CCP1
      delay_ms(5);
      set_pwm2_duty(duty2); // RC1=CCP2
      delay_ms(5);

    // GO REVERSE
    } else if ( y < (YCENTER - 12) ) {
      // RR code
      RR();
      yduty = (1 - (y/(YCENTER))) * 1023.0;

      duty2 = yduty;
      duty1 = yduty - ((xduty/1023) * yduty);

      // set pwm duty
      set_pwm1_duty(duty1); // RC2=CCP1
      delay_ms(5);
      set_pwm2_duty(duty2); // RC1=CCP2
      delay_ms(5);

    } else {
      // RR code
      RR();
      //setduty1 = (xduty/1023) * yduty;
            duty2 = xduty;
            duty1 = 0;
      // set pwm duty
      set_pwm1_duty(duty1); // RC2=CCP1
      delay_ms(5);
      set_pwm2_duty(duty2); // RC1=CCP2
```

```
        delay_ms(5);
              }

  // TURN LEFT
  } else if ( x > (XCENTER + 16) ) {
      // set xduty
      xduty = (1 - ((255 - x)/(255 - XCENTER))) * 1023.0;

      // set direction
      // GO FORWARD
      if ( y > (YCENTER + 32) ){
        // RF code
        RF();
        yduty = (1 - ((255 - y)/(255 - YCENTER))) * 1023.0;

        duty1 = yduty;
        duty2 = yduty - ((xduty/1023) * yduty);

        // set pwm duty
        set_pwm1_duty(duty1);
        delay_ms(5);
        set_pwm2_duty(duty2); // RC1=CCP2
        delay_ms(5);

      // GO REVERSE
      } else if ( y < (YCENTER - 12) ){
        // RR code
        RR();
        yduty = (1 - (y/(YCENTER))) * 1023.0;

        duty1 = yduty;
        duty2 = yduty - ((xduty/1023) * yduty);

        // set pwm duty
        set_pwm1_duty(duty1);
        delay_ms(5);
        set_pwm2_duty(duty2); // RC1=CCP2
        delay_ms(5);


      } else {
        // RR code
        RR();
        //setduty1 = (xduty/1023) * yduty;
              duty1 = xduty;
              duty2 = 0;
```

```
          // set pwm duty
          set_pwm2_duty(duty2);
          delay_ms(5);
          set_pwm1_duty(duty1);
          delay_ms(5);
                  }

     // STRAIGHT (NO TURNING)
     } else {  // (x > (XCENTER - 16)) &&(x < (XCENTER + 16) )
       // GO FORWARD
         if ( y > (YCENTER + 32)){
                  // RF code
         RF();
         yduty = (1 - ((255 - y)/(255 - YCENTER))) * 1023.0;
           duty1 = yduty;
         duty2 = yduty;
         // set pwm duty
         set_pwm1_duty(duty1); // RC2=CCP1
         delay_ms(5);
         set_pwm2_duty(duty2); // RC1=CCP2
         delay_ms(5);
         }
       // GO REVERSE
         else if ( y < (YCENTER - 12)){
                  // RR code
         RR();
         yduty = (1 - (y/(YCENTER))) * 1023.0;
           duty1 = yduty;
         duty2 = yduty;
         // set pwm duty
         set_pwm1_duty(duty1); // RC2=CCP1
         delay_ms(5);
         set_pwm2_duty(duty2); // RC1=CCP2
         delay_ms(5);
       // STOP
         }        else {
                  stop();  // make stop code a function
         }
     }

   } // end while loop

} // end main();

// Other Functions, defined previously above main();
void stop(){
```

```
    // ground stop reverse
    //output_low(pin_D7);
    //delay_ms(5);

    // ground stop forward
    //output_low(pin_D5);
    //delay_ms(5);

    // float run forward
    output_float(pin_D4);
    delay_ms(5);
    // float run reverse
    output_float(pin_D6);
    delay_ms(5);

    duty1 = 0;
    set_pwm1_duty(duty1); // RC2=CCP1
    delay_ms(5);

    duty2 = 0;
    set_pwm2_duty(duty2); // RC1=CCP2
    delay_ms(5);

}
void RF(){
//insert RF code
        //output_float(pin_D5); // unground SF
        //delay_ms(5);

        // toggle run forward
        output_low(pin_D4); // ground run forward
        delay_ms(5);
        //output_float(pin_D4); // float run forward
        //delay_ms(5);
}
void RR(){
//insert RR code
        //output_float(pin_D7);  // unground SR
        //delay_ms(5);
        // toggle run reverse
        output_low(pin_D6); // ground run reverse
        delay_ms(5);
        //output_float(pin_D6); // float run reverse
        //delay_ms(5);
}
```

Appendix G

American Wire Gage Standards

AWG gauge	Diameter Inches	Diameter mm	Ohms per 1000 ft	Ohms per km	Max amps for chassis wiring	Max amps for power transmission
OOOO	0.4600	11.6840	0.0490	0.160720	380	302
OOO	0.4096	10.40384	0.0618	0.202704	328	239
OO	0.3648	9.26592	0.0779	0.255512	283	190
0	0.3249	8.25246	0.0983	0.322424	245	150
1	0.2893	7.34822	0.1239	0.406392	211	119
2	0.2576	6.54304	0.1563	0.512664	181	94
3	0.2294	5.82676	0.1970	0.646160	158	75
4	0.2043	5.18922	0.2485	0.815080	135	60
5	0.1819	4.62026	0.3133	1.027624	118	47
6	0.1620	4.11480	0.3951	1.295928	101	37
7	0.1443	3.66522	0.4982	1.634096	89	30
8	0.1285	3.26390	0.6282	2.060496	73	24
9	0.1144	2.90576	0.7921	2.598088	64	19
10	0.1019	2.58826	0.9989	3.276392	55	15
11	0.0907	2.30378	1.2600	4.132800	47	12
12	0.0808	2.05232	1.5880	5.208640	41	9.3
13	0.0720	1.82880	2.0030	6.569840	35	7.4
14	0.0641	1.62814	2.5250	8.282000	32	5.9
15	0.0571	1.45034	3.1840	10.44352	28	4.7
16	0.0508	1.29032	4.0160	13.17248	22	3.7
17	0.0453	1.15062	5.0640	16.60992	19	2.9
18	0.0403	1.02362	6.3850	20.94280	16	2.3
19	0.0359	0.91186	8.0510	26.40728	14	1.8
20	0.0320	0.81280	10.150	33.29200	11	1.5
21	0.0285	0.72390	12.800	41.98400	9	1.2
22	0.0254	0.64516	16.140	52.93920	7	0.92
23	0.0226	0.57404	20.36	66.78080	4.7	0.729
24	0.0201	0.51054	25.67	84.19760	3.5	0.577
25	0.0179	0.45466	32.37	106.1736	2.7	0.457
26	0.0159	0.40386	40.81	133.8568	2.2	0.361
27	0.0142	0.36068	51.47	168.8216	1.7	0.288
28	0.0126	0.32004	64.9	212.8720	1.4	0.226

Appendix H

Bill of Materials

Material	Supplier	Quantity	Cost Per Item	Total
Joystick	Bruce Maxwell	1	stock	0.00
PIC microcontroller(s)	Engin Dept	tbd	stock	0.00
Motor Controllers	KB Electronics	2	272.00	272.00
12V-40Ah Batteries	BatteryMart.com	2	49.95	49.95
24V Motors	Groschopp	2	347.00	694.00
Mini Battery Switch With Knob	Overtons	1	19.99	19.99
10-gauge Semi-Circle Lugs	Engin Dept	1(packet)		7.00
10-gauge Stranded Wire (Red)	Engin Dept			26.98
Vectra Bike Computer	Erik Cheever	1	yard sale?	0.00
Magnet For Bike Computer	Carr Everbach	1	stock	0.00
digital shaft encoder	Engin Dept	tbd	stock	0.00
Castor Wheel	Acorn	1	40.00	40.00
Tires	Surplus Center	4	10.00	40.00
Chain	Engin Dept	1	tbd	4.00*
Sprockets	Engin Dept	4	tbd	7.00*
Pillow Blocks	Engin Dept	tbd	tbd	30.00*
PVC		1	stock	0.00
Plastic Classroom Seat	Engin Dept	1	stock	0.00
2X2inch 3/16" wall Aluminum Tubing	Engin Dept	tbd	tbd	100.00*
1/4" plating		tbd	tbd	tbd
3/16" Aluminum Plating	Engin Dept	stock	stock	0.00
Aluminum 5/16" All-Thread	Engin Dept	tbd	tbd	tbd
Aluminum Rod	Engin Dept	stock	stock	0.00
Plunger	Engin Dept	1	30.00	30.00
Total Expenditure				**1321.00**

* price values are estimates.

Appendix I

References

Background Research

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Hoseinnezhad, Reza and Alireza Bab-Hadiashar. Missing Data Compensation for Safety-Critical Components in a Drive-by-Wire System. IEEE Transactions on Vehicular Technology, Vol. 54, No.4, July 2005

Kattamis Alex et al. E-Racer, a Joystick Controlled Go-Kart. Proceedings of the IEEE Anuual Northeast Bioengineering Conference, 2001

General

http://www.twike.com/

http://www.cloudelectric.com/generic.html?pid=66

http://www.eaaev.org/Forms-Docs/eaaflyer-evconversions.pdf

http://www.electroauto.com/

http://www.epanorama.net/links/motorcontrol.html

http://www.automotivedesignline.com/howto/chassisandsuspension/165600237;jsessionid=PAYFTRIHWV5R4QSNDBCCKHSCJUMEKJVN

http://www.gmecca.com/byorc/dstratdesignapproaches.html (Design Approaches)

http://www.electric-bikes.com/DIY.htm

EV and Go Karts

http://www.econogics.com/ev/evkarts.htm (links)

http://store.razorama.com/grfoelgoka.html
(razor gokart, unit wt 70lbs (+ ?) two 12V lead acid batteries)

http://home.comcast.net/~briano911/gokart.html (home-made, electric off road kart)

http://www.mfgsupply.com/GoMiniKits.html/mv_session_id=K4iDPnNo
(commercial go-karts)

http://www.planetgrind.com/jump.jsp?itemType=CATEGORY&itemID=631&path=631
(commercial go-karts)

http://www.electricgocarts.com/www-electricgocarts-com/pricelist.htm
(see price of commercial go kart)

http://www.allwebscooters.com/mobility_chair.asp (wheel chairs)

http://www.rqriley.com/doran.html (gas or electric 3 wheel car)

http://www.seas.upenn.edu/~triangle/issues/85-01/solarcar.html (solar car)

PIC

http://www.swarthmore.edu/NatSci/echeeve1/Ref/C%20for%20PIC/C_Intro.html

Motor Controllers

http://www.4qd.co.uk/faq/current.html (January 11, 2006)

Motors

http://www.lemcoltd.com/lem_200.htm (Lynch motor, 200)

http://www.magmotor.com/C40.htm

http://www.shinano.com/xampp/skvconv.swf (conversions, calculations)

http://lancet.mit.edu/motors/motors4.html#2.007ts (calculations)

http://www.globe-motors.com/dc_motor.pdf (about dc motors, calculations)

http://www.electricmotors.machinedesign.com/Electric-Motors-Reference-Center.aspx (electric motor suppliers)

Batteries

http://www.batteryweb.com/wheelchair.cfm

http://store.solar-electric.com/cosuagmba.html http://www.batterymart.com/battery.mv?c=wheelchair_batteries

http://www.batterymart.com/battery.mv?c=sla-12volt

http://www.batterymart.com/battery.mv?c=deep_cycle_marine_batteries

http://www.powerqualityinc.com/batterys.htm

http://www.asmokarts.com/

http://www.windsun.com/Batteries/Battery_FAQ.htm

http://www-ee.eng.hawaii.edu/~hevsim/Battery/ (electric vehicle battery simulator)

Tires

http://www.mentor.com/products/sm/systemvision/automotive_electrical_systems/index.cfm

http://www.virtualtechnologiesltd.com/FAQs/Battery%20FAQ.htm

http://specialtytirestore.com/go_krt_1_ass.htm (C165 Cheng Shin Turf Tires - 16x6.50-8, 4 ply. Set of 2 tires, $64.00)

http://www2.northerntool.com/product-1/12790.htm

Other resources (a sampling…)

Emadi, Ali, et al. Vehicular Electric Power Systems: Land, Sea, Air, and Space Vehicles. Marcel Dekker, Inc: New York, 2004.

Larminie, James, and John Lowry. Electric Vehicle Technology Explained. John Wiley & Sons, Ltd: United Kingdom, 2003.

Wong, J.Y. Theory of Ground Vehicles. John Wiley & Sons: New York, 1978.