Design of an affordable electric snowmobile — Done Right

Michael Golub, Isaac Thompson, Adam Burnette, Russell Carroll, Amanda Mertes, Benjamin Neubauer, Craig McKenzie, Karlin Swearingen
University Alaska Fairbanks

ABSTRACT

The University of Alaska Fairbanks Nanook EV team's latest electric snowmobile has a 51.5 km (32 mi) range at 32 km/h (20 mi/h) under optimal snow conditions. Building on the 2011 competition success (winning Best Design with a Ski-Doo Tundra 300F), we started this project with a much improved chassis: a Ski-Doo Renegade Sport 550F (Figure 1) (wet weight: 232 kg (512 lb)). The modified NetGain WarP 7 DC-series motor is connected directly to the sprocket shaft using a Gates Poly Chain. The accumulator is configured to support 177.6 V using 72 Turnigy 5 A·h lithium-ion polymer hybrid cells, which utilize a gel electrolyte. The battery box, containting the 7.992 kW·h accumulator, comes off as one piece.
Innovation was a key design concept as the team developed the first electric snowmobile on the Ski-Doo RevXP Chassis. This was a difficult design challenge with its tight pyramidal frame; however the result is having one of the most efficient snowmobile chassis available, running on electric power. The design allowed for any part to be easily removed and replaced. The team developed a robust Battery Management System (BMS) based on the Peter Perkins open source work. This innovation consisted of modifying the programming for a user display that contains battery information, power monitoring and speed. Not content with current DC motor controllers the team utilized the Open ReVolt plans to come up with a reliable and safe unit. The 137 inch suspension was retained to allow for use of the GTX silent track technology and assist during the drawbar pull. Our innovations have kept our MSRP the lowest amongst the competition sleds. The snowmobile weighs a respectable 250 kg (550 lb) and has a top speed of 120 km/h (75 mi/h) and a noise level of less than 60 dB. This snowmobile is poised to do very well in the competition. Table 1 summarizes our goals.

Table 1: UAF Goals for CSC 2011

Category	Challenge Record	UAF Goal	UAF Has Obtained
Range	32 km (20 mi)	30 km (18.6 mi)	>30 km (18.6 mi)
Weight	226 kg (498 lb)	250 kg (550 lbs)	<250 kg (550 lbs)
Drawbar Pull	3.74 kN (841 lbf)	2.6 kN (590 lbf)	>2.6 kN (590 lbf)
Noise*	57 dB	60 dB	<60 dB
MSRP	$11.8K	$15K	~$16K

*With studded track

INTRODUCTION

The National Science Foundation (NSF) supports research in Polar Regions, which are extremely sensitive areas that are highly impacted by pollution. In 2005 the Clean Snowmobile challenge added the additional category: "Zero-Emissions" in order to promote the use of vehicles which would not contaminate the fragile environments in these regions [1]. Also, it was important to avoid contaminating samples taken from these areas, as engine fumes could adversely affect the samples. Our team was also motivated to design an affordable electric snowmobile due to local high energy costs in Alaska. Gasoline is a precious commodity in rural villages across the state, many of which are not connected to a road system. The price of a gallon of gasoline can be in the $ 10 range. Fuel is shipped to Alaskan villages in the summer by barge when the rivers and other shipping lanes are ice free. In some areas, fuel needs to be flown in, increasing the price even more [2]. The Nanook EV team has focused on finding transportation solutions for rural Alaska that can help reduce villagers' energy consumption, but still maintain their way of life. Electric vehicles have been a very promising solution when paired with locally generated renewable power. The team envisions clean, efficient electric vehicles used as primary local transportation, powered by renewable energy such as geothermal, wind and hydropower. These resources are abundant in rural Alaska but are currently under-utilized. Our snowmobile is designed for the most practicality and performance that an electric sled can offer. At the same time, we strove to demonstrate that electric vehicles can be a viable option for certain applications. To accomplish this, an “innovative, quicker, inexpensive” design philosophy was adopted. The goal was to produce a system that had impressive performance, while still being affordable and easily accessible to the general public. This is our fourth year in this competition, and we offer an improved vehicle that is light and comfortable for the rider, along with additional modifications to the original chassis, all while maintaining a clean, flexible, and aesthetically pleasing design. Snowmobiles are an indispensable means of winter transportation in rural Alaska. While these machines are primarily used for recreation in the rest of the country, here they are an important tool that makes life in remote villages possible. Snowmobiles are therefore an ideal candidate for electric conversion. The Nanook EV team has extensive experience in converting traditional vehicles to run on electric power. Members of the team have converted everything from cars and trucks to ATVs and lawn mowers [3].

DESIGN STRATEGY

The main design strategy was to convert the snowmobile to be most successful at the competition. This year’s competition scoring is more in line with National Science Foundation (NSF) contractor desires. Currently, over 57% of the events relate directly to their needs to support arctic research. The restriction of the accumulator size is an interesting complexity, however, the 8 kW·h size has been successful in doing 14 mi runs in Greenland, and UWM did a successful 20 mi run last year. The acceleration event has been modified. We still needed a high power density battery for the straight-aways, which would benefit our machine on the objective handling track. We were unsuccessful in obtaining cutting-edge batteries that boasted mass energy density of over 300 W·h/kg. These include many lithium-ion based batteries using elements like sodium and silicon. We even sought some semiconductor batteries. What we settled on was an inexpensive pack of lithium cobalt ($LiCoO_2$), which fit in nicely with our light-weight chassis. This keeps our overall cost low for our final Manufacturer’s Suggested Retail Price (MSRP).

Figure 1: 2011 Ski-Doo Renegade Sport 550F in unmodified form.

Our primary goal was to boast our innovations for this project. We had incentive to keep the modification as simple as possible while using available and affordable parts. The parts needed to be low cost yet durable. Emphasis was added on using the best and least expensive parts to make our motor controller, BMS and other key components. This not only would keep the MSRP low, but allow repeatability and ease for a pre-fabricated kit to be manufactured, so other users could enjoy and benefit from the use of an electric snowmobile. Although electric sleds have been emphasized in past competitions as tools for research purposes, our sled would also be ideal for the general public. Uses could include transportation to work in rural areas, checking trap-lines, subsistence hunting and fishing, and grooming ski and dog sled trails. We wanted a snowmobile that riders would want to use. Consumers are mostly interested in cost and range, and we feel we have achieved a snowmobile that meets those criteria.

Historically, it is interesting to note that dog mushing had been a common transportation choice in Alaska until the mid-1970s. Dog teams were used by the Postal Service in remote villages until the 1960s. The U.S. Army (Figure 1) and the National Park Service maintained sled dog teams for rescue missions or patrolling in remote areas. Denali National Park still employs a dog team today since motorized vehicles are not allowed in certain areas of the Park. With the advent of the snowmobile, Alaskans and other northern locals became enamored with this new machine; however, travel could be dangerous if the snowmobile broke down or ran out of fuel. An electric snowmobile offers a few different options. While the batteries may run out, the machine probably is not too far away from help. Also, the snowmobile could be equipped with an on-board emergency generator to provide enough power to limp home. But perhaps the most exciting option would be for the machine to carry either a hydro or wind turbine that could be setup when the snowmobile was stationary. The use of portable solar panels was also considered, but solar is not a viable option for several reasons. Arctic regions enjoy little sunlight in the winter, and current solar panel technology is very inefficient and would require a trailer that is 12 m (40 ft) long to accommodate the number of panels required.

INNOVATION

Innovation was a key design concept as the team developed the first electric snowmobile on the Ski-Doo RevXP Chassis. We designed and built several major innovations:

1. Newer chassis to modify caused unique challenges because of its tight pyramidal frame. Working without a tub makes finding space for items more difficult. However we designed it so any part of the machine can be easily removed and replaced. Some examples of these include the BMS master unit and the 12V auxiliary box. Either (or both) of these can be removed in less than 1 minute using only a 10mm nut driver. The traction pack itself can also be removed as a single unit, without disconnecting fusing or sensor.
2. The team developed a robust BMS based on the Peter Perkins open source efforts. This innovation consisted of modifying the programming for a user display that contains battery information, power usage and speed.
3. Not content with current DC motor controllers the team utilized the Open ReVolt plans to come up with a reliable and safe unit.
4. We can charge through the 12 V accessory port, eliminating a separate 12 V charging jack.

BATTERY MANAGEMENT SYSTEM

We adapted our own version of a battery management system. There are many systems commercially available, but none of them offered the compact size, affordable price, or flexibility that our design criteria demanded. Some available BMS systems and their price per cell are shown in the Figure 2.

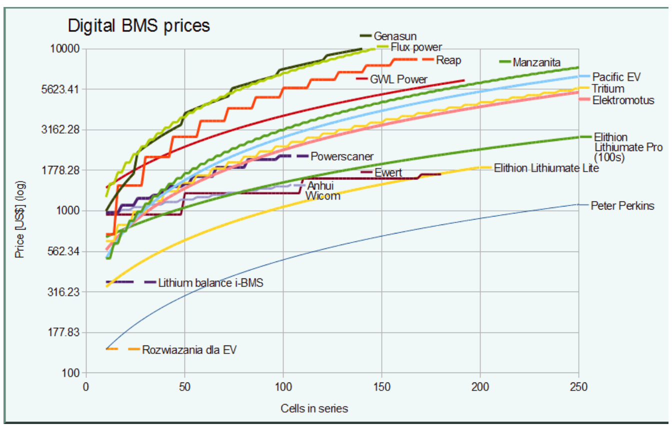

Figure 2: Cost comparison chart of commonly available BMS systems

Electrically, much of our design is based on the work of Peter Perkins, who started his own BMS project in 2007. We have followed his work very closely, and have adapted his system to fit our battery. Changes to the original design include software edits to handle the voltages associated with different battery chemistry, as well as modifying the temperature monitoring and current sensing routines. Future changes will likely involve cell board layout, adapting a surface mount design instead of the current through-hole design. This will allow many more cell monitors to fit on the same board in a much smaller area.

Presently, the BMS monitors cell voltage, pack current, pack temperature, and vehicle speed. It uses this information to display total pack voltage on screen, along with highest and lowest cell voltage (and their cell numbers.) It also tracks and displays total current in and out of the pack, and uses this to display pack state of charge (SOC). Additionally, the BMS displays instantaneous power being supplied by the battery, as well as instantaneous energy use per distance (in units of [W·h]/mile). In addition to monitoring pack condition and displaying relevant information, the BMS is also able to control basic vehicle functions. During charging, individual cell voltage is monitored, and throttles the charger back to a trickle charge state so that cells can top balance. The BMS cell boards are capable of balancing at 500 mA per cell. When all cells have reached the balancing phase, the charger is shut down completely.

During discharge (while the machine is in use) the BMS monitors cell voltage and watches for a low voltage condition on any cell. When the first cell reaches a low voltage condition, the BMS will throttle the controller back. This alerts the driver that the pack is almost empty and needs to return to a charging station immediately, allowing the vehicle to be driven to a safe location in “limp”-mode. However, if any battery cell goes under a pre-set "absolute minimum" voltage, the controller is shut down completely in order to keep from damaging the battery by over-discharging it. In daily use the battery should never be discharged to absolute minimum, but if it does happen, the BMS will ensure that catastrophic damage does not occur. Additionally, this same shut-down procedure is enacted if pack temperature ever goes over a set max temp, such as if the battery were being worked too hard for too long. Because the shutdown procedure consists of opening the main contactors, this will also prevent the pack from overheating in the event of a short circuit or overcharging situation.

Figure 3: (a)Secondary boards monitor up to 16 cells each (b)Master board accepts input from secondary boards, and performs calculations (c)Master unit displays battery pack and cell voltage information

MOTOR CONTROLLER

The open source motor controller is the heart of the machine. Without the proper controller, the snow machine would have poor performance and render the machine unpractical. The choice of going with the open source motor controller was made for cost and the ability to redesign and modify the controller as required. The open source motor controller project, known as the ReVolt controller [19], got its start in electric car conversions. It was designed to be a low-cost high-performance alternative to existing expensive “dumb” controllers. Most DC motor controllers available in the $ 1 500 category were just very simple analog switching circuits that would take a throttle signal and create a torque command proportionally to drive the traction motor. Torque control was chosen because this is the form of control that a normal combustion engine uses.

Some of the flaws of these controllers are their switching frequency. At high temperature or low duty cycles (small amounts of throttle) the controllers would drop from a switching frequency of 15 kHz to 1 kHz. This would create less heat in power stages due to the smaller amount of transitions of the switching devices per second. The downside to this “feature” is it causes an audible wine in the motor when in this mode. While some people like this to make the vehicle more noticeable to pedestrians, one of the coolest things of an electric vehicle is it can move with almost zero noise. For this reason, the ReVolt controller was design to run at 16 khz. The Revolt controller never changes out of this switching frequency, but instead limits power output if the controller in 8 steps starting at 75 ºC and full shutdown at 95 ºC. As the controller cools down, output will be restored using the same 8 steps but inverted.

The Revolt controller possesses microprocessor control, communication port and extensive safety features. The Atmega168 microprocessor chosen was based on cost, performance, and programming simplicity. This is one of the many AVR based microprocessors. It was set up to run at 16 MHz allowing the 15.625 kHz Pulse Width Modulated (PWM) output frequency as well as 16 kHz interrupt clock running inside the chip to keep functions happening at specific, time sensitive intervals. The communication port is a standard RS-232 protocol running at 19200 baud 8,N,1 allowing devices that supports the RS-232 protocol to talk to the controller. The software runs with a real time data stream that outputs all the values the controller is reading from external sensors and it is internally generated at a user defined interval from 1 ms to 9999 s intervals. Also, all the throttle adjustment and trip point settings, and current limit settings are available through this interface.

Because of the processing power extensive safety features were developed. A major feature is the ability to check multiple inputs for out of range and strange anomalies. In such a case the power stage would be shut down so nothing bad could happen. These inputs include throttle value checking, current sensor value checking and under voltage lockout protection. If any of these values output out of range, the controller will fault and shut down. The current sensor being the most important sensor in the controller, it is treated with more diligence. When the controller is powered up, there is a small delay for the output of the current sensor to stabilize, and then a reading is taken. Since the sensor is designed to output 2.5 V at 0 A, if this first reading is outside this range, the controller will fault immediately. Without a working current sensor, there is no way for the controller to regulate power from the batteries to the motor, thus making the vehicle unsafe to operate. Since the controller is a torque controlled, and torque is proportional to the amount of current being fed into the motor, without a way to measure current, there is no way to control torque. If the current sensor breaks during operation or becomes disconnected, the software will sense this and shut down the output.

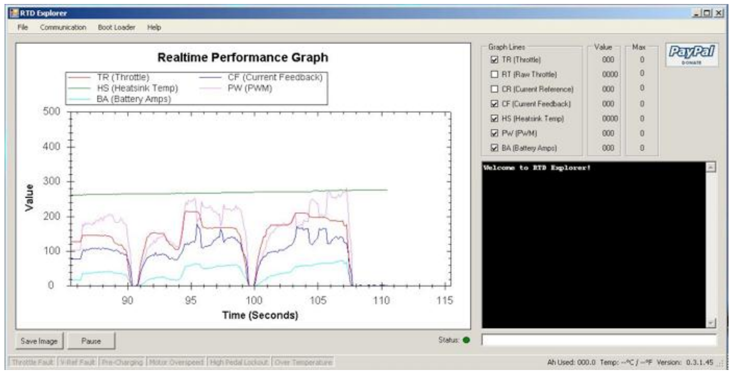

Figure 4: RTD Explorer provides many features for the open source ReVolt Controller

We improved the motor controller's logic board. We built a controller that was on the leading edge of innovation using some of the highest quality parts while still being cost conscious. To achieve our goals we decided to go with a film capacitor and bus plate power stage using half bridge Insulated Gate Bipolar Transistor (IGBT) switching devices. This would allow us to keep the form factor relatively small while achieving incredibly high performance. Our design requirements include the ability to withstand a nominal battery pack voltage of 201 V and achieve a sustained 600 A motor current while being able to handle acceleration loads of 1 000 A. To accomplish this, we decided to go with an SB Electronics Power Ring film capacitor. This capacitor features an extremely high handling ripple current. The film feature uses no electrolytic which is prone to drying out. The capacitor has eight terminals per pole allowing super low inductance. This is very important in motor controller designs to reduce inefficiencies. By using this capacitor, we have the ability to use a design technique known as laminated bus design. This consists of a plate of copper sandwiched with a layer of insulating substrate. This again leads to a super low inductance design as the two power planes are as close to each other as physically possible. Three IGBT modules are placed right to the side of the capacitor. The plates connect to the terminals of the modules and the capacitor with copper spacer washers and brass screws. Some of the holes in the plates are oversized to allow them to fit around things like terminals or washers and allow isolation while others contact thermals directly. This allows all the connections to be made without bending the plates out of shape. The only external connections that need to be made would be the two battery connections and the two motor connections.

The IGBT modules are controlled by a custom designed Powerex VLA-501 12A driver module. The dual voltage output of the driver module is specific to IGBT modules. To turn an IGBT off quickly, you must use a negative voltage. The VLA-501 switches the gate of the module from -8.2 V at off to an on of 15.8 V. This allows for strong gate signals and high noise immunity. This module features full isolation design and includes an onboard DC-DC converter that takes 15 V input and creates 15.8 and the -8.2 V for driving the IGBT's. The driver board commands all three IGBT's in parallel and is optimized for matched inductance and delay to each module. This allows all the modules to turn on within nanoseconds of each other allowing all 3 modules to share current evenly. By building our own controller, we were able to suit our needs perfectly while achieving the performance of controllers that cost over $3 600. Our MSRP cost for this controller was less than $ 560.

Using open source design has the benefits of collective productivity. We created a rough concept for RTD Explorer, and now it exists. This program uses the serial communication connection of the controller. It features real time graphing, with data logging, configuration and firmware upgrading, all in one easy to use interface. The graphing feature takes advantage of the real time data stream, coming from the controller, generating line graphs of: throttle, motor current, battery current, heat sink temperature and duty cycle. This allows for easy diagnostics and view of the commands and control values in the controller. Data is pulled every 0.1 s, ensuring a very smooth update rate. Other useful features are the ability to export the data stream to a CSV file to be opened later on in a spreadsheet program. The program also displays all fault codes that are active in the controller, which makes it very easy to see what is going wrong. Lastly, the program contains an interface to the boot loader utility, which allows easy field upgrade of the controller's firmware. All that is required is to select the file you want to upgrade to, and select the start boatload option and the program takes care of the rest. First, it restarts the controller, then loads and verifies the new software and finishes by starting the restarting the controller. This can all usually take place within 30 seconds.

FUSING

Creating a safe and rule compliant snowmobile was a challenge we undertook extra seriously this year. We engineered our own fuses. A strip board, backed with flame-retardant electrically-insulated heat-conductive epoxy (50-3150FR) (See Figure 5). They passed our test conditions to blow at 3 A - 8 A. The battery leads and connectors were tested at the same time and did not get hot before the "fuse" blew. We also designed and built our own fuse holder which holds nine 100 A secondary fuses, and a 400 amp main fuse.

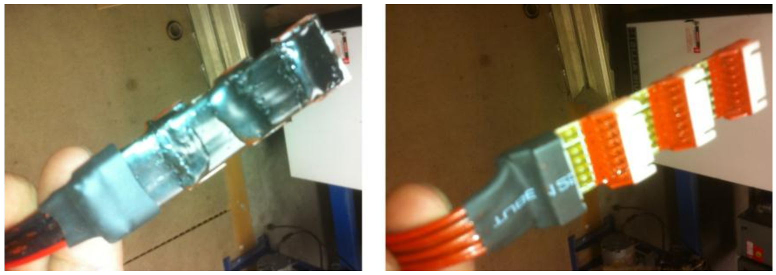

Figure 5: A strip board, backed with flame-retardant electrically-insulated heat-conductive epoxy.

ENERGY STORAGE REVIEW

For the last two years to attain sufficient range, we placed great importance on obtaining the largest energy storage capacity possible. Batteries generally available for traction applications consist of metals such as lead, nickel and lithium. Thomas Edison designed the first traction batteries using nickel iron (NiFe) [4]. His battery (and his electric car) was later replaced with lead acid batteries (PbA) in the early 20th century. The nickel battery has evolved to such variants as the nickel cadmium (NiCd) and nickel metal hydride (NiMH) battery. Using nickel was an improvement over lead, except for cost and safety to the end user. Both lead and nickel exhibit a poor mass energy density of under 75 W·h/kg. However, when using the lightest metal available, lithium batteries promised excellent mass energy density. At first, a non-rechargeable lithium battery was developed and dubbed "Lithium Metal". When the first lithium secondary cells were promoted, they were distinguished from non-rechargeable primary cells as "Lithium-Ion", or "Li-Ion." Today there are four major types of Lithium rechargeable batteries in production and available for resale. They are: lithium cobalt ($LiCoO_2$), lithium manganese ($LiMn_2O_4$), lithium nickel ($LiMn_xNi_yCo_zO_2$), and lithium iron phosphate ($LiFePO_4$). Table 2 shows various cell attributes.

Table 2: Battery Chemistry Examined

		Nickel		Lithium-ion			
Criteria	Lead Acid	NiCd	NiMH	$LiCoO_2$	$LiMn_xNi_yCo_zO_2$	$LiFePO_4$	LiPoly Hybrid
Mass Energy Density (W·h/kg)	35	40	75	180	160	110	140
Volume Energy Density (W·h/L)	68	50	200	250	250	220	286
Power Density (W/g)	0.18	0.15	0.7	3	3	3	4.2
Cycle efficiency (% charge/discharge)	70	70	70	95	95	95	95
Self-discharge (%/month)	10	10	30	5	5	5	3
Cycle life (total cycles)	200	1000	500	500	500	2000	1000
Current cost (US Dollar/W·h)	$0.05	$0.23	$0.47	$0.60	$0.60	$0.31	$0.40
Nominal Voltage	2.1	1.2	1.2	3.7	3.7	3.2	3.7
BMS Required	No	No	No	Yes	Yes	No	Yes
Environmental	Poor	Bad	Good	Average	Average	Good	Good
Cost based on cycle life x W·h of Lead	1	0.7	1.3	1.75	1.75	0.2	0.45

For the first two years our team used lithium iron phosphate batteries. Using them kept our MSRP and our build budget low. At the time we decided they were a better alternative to lithium cobalt batteries because of its environmental benignity, its abundance, and the fact that it was less expensive than $LiCoO_2$. Additionally, the redox couple Fe^{+3}/Fe^{+2} is conveniently located at 3.45 V with respect to Li^{+1}/Li, and is compatible with many organic and polymer electrolytes. The successful commercialization of $LiFePO_4$ happened due to its high electrochemical performance, particularly in terms of reversible capacities. The initial problems of low electronic conductivity and low Li-ion diffusion rates have been improved significantly by co-synthesizing it with conductive sources, and making the particle size smaller, which resulted in diffusion path reduction [5].

This year, like last year, we decided to use lithium batteries that are used by many Remote Control (RC) hobbyists. RC LiPo batteries are a hybrid lithium polymer battery. The correct name for this type of battery is lithium-ion polymer, but the battery world of today simply calls them lithium polymer even though they are not a true dry type LiPo battery. By introducing a gelled electrolyte into the polymer, the ion exchange rate is improved. Since the electrolyte is gelled, there is less chance of leakage, but it is still flammable. LiPo hybrids are not as dangerous as Li-Ion's but they can still catch fire or explode if over charged, shorted, or punctured. When first introduced, LiPo batteries were more expensive than Li-Ion because they are more difficult to manufacture. Prices have dropped substantially. LiPo hybrids use the same flat cell structure as their dry counter parts meaning they have the same flexibility with sizes and shapes.

RC LiPo battery cell is packaged in a foil pouch coincidentally called a pouch cell [6]. Again, our team chose the lithium-ion polymer for our electric snowmobile. Our primary reasons were mass energy density, availability and cost. These batteries are the least expensive lithium batteries available based on mass energy density. We installed 72 Turnigy batteries. These batteries have a 22.2 V nominal voltage. Connecting eight of these batteries in series gives us the 177.6 V. We have a total of nine series strings which are then parallel connected. Each string has an individual fuse [7]. Higher voltages allow a smaller amount of current, which produces less heat and less wasted energy. The batteries were confirmed to exhibit a low internal resistance during loading. Resistance values per battery are 0.003 Ω. Having a low internal resistance allows the snowmobile motor to draw more power. This is a huge improvement when compared to lead acid batteries. Charger efficiency is also increased because less energy is wasted in heat.

ENERGY STORAGE CONTAINERS

In order to safely house all the batteries necessary to meet the range goal, a robust energy storage containment system was designed and fabricated. To ascertain whether or not the battery box could withstand any possible impact the snowmobile would experience, the battery box was computer modeled using 6 mm (0.236 in) polycarbonate (figure 4). This material has a young's modulus of 3.2 GN/m, and a density of 1.20 g/cm. The box was modeled to withstand an impact at 32 km/h (20 mi/h), with the 249 kg (550 lb) of snowmobile compressing the box. This model shows that this material was strong enough to meet our needs. The results show that the box did not deform beyond its set limit. As with all the other components added, the location and construction of the energy storage containers contribute to the reproducibility and practicality of the design.

DRIVE TRAIN

The gasoline engine is removed, along with the continuously variable transmission (CVT), the fuel tank, the muffler, and other associated parts. These are replaced with a Net Gain WarP 7 DC series motor, a 201 VDC ReVolt Motor Controller, a 177.6 V battery, a Gates Poly Chain GT Carbon V-Belt (8MGT-1000-36), C3 Powersports 63-tooth bottom gear and Gates (PB8MX-25S-36) top gear. Another way to increase the range of the design was to increase the drive train efficiency. The original CVT in the snowmobile was designed to keep the internal combustion engine operating at its optimal range. This however, is not an issue with an electric motor as a power source. Electric motors are capable of operating effectively at a much wider range of operating speeds. This property, combined with the ability of an electric motor to spin freely even when electrical power is not being supplied, allowed the use of a much more efficient direct drive system. Not removing the CVT can cause a decrease of performance by 20 %. Removal of the chain case and jack shaft means that the snowmobile will require only two fluids: brake fluid and bearing grease. This makes a cleaner vehicle. It also reduces weight, and allows a simpler redesign.

Table 3: Belt Design Criteria

Option	Cost	Simplicity	Eff.	Noise
V-Belt	Low	Yes	Good	<60dB*
Gates Poly Chain	High	Medium	Best	73 dB
Goodyear Eagle	High	No	Best	69 dB

**At rated power*

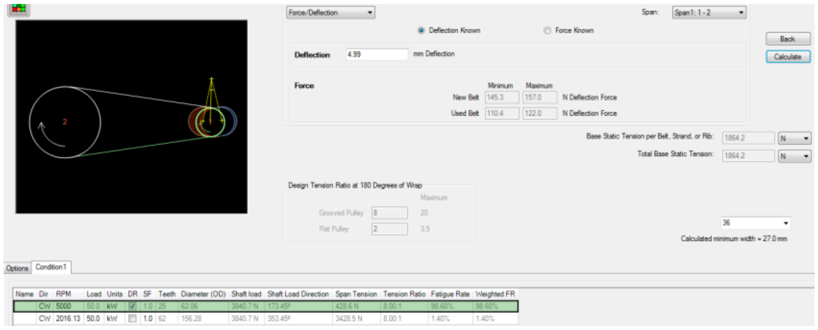

Figure 6: Gates Design IQ3 drive system analysis tools used to calculate minimum belt width.

With the chain case removed we had three choices for belts. These are Standard V-Belt, and two synchronous belts: Gates Poly Chain or a Goodyear Eagle Synchro belt (Table 3). The Synchronous belts afford a better efficiency of 98 %, while the V-Belt slippage classified them with a 95 % rating. Synchronous belts also make 73 dB of noise whereas V-Belts have potential to much lower in noise. On the other hand, V-Belts cannot do as much power. In the end the design team went with the Gates Poly Chain. The power requirements of this competition do not merit the use of the V-belt. Using Gates Design Flex Pro software [9], the minimum gear diameter and belt type was chosen. In Figure 6, Gates Design IQ3 drive system analysis tools were used to calculate minimum belt width, given a load of 50 kW at 5 000 rev/min. This is more than double what our motor is rated to put out, giving us a margin of safety, while still allowing us to use an extremely lightweight system.

MOTOR IMPROVEMENTS

We installed Helwig-Carbon red-top brushes, increased the spring pressure and used World Wide Bearings ceramic bearings. These design upgrades for the motor increased efficiency by 3 %. The Red Top design is more efficient because it helps to make better contact with the commutator, producing less voltage drop and less “unsafe” arcing. Less voltage drop allows for more voltage to get to the armature windings, making the motor more powerful and efficient. The Red Top design can be made with many different carbons and the composition of the brush material will also make a difference in the voltage drop to the commutator and the motor efficiency. Brush grade H60 was chosen for cold weather applications. Because this traction motor is in a vehicle that is subjected to rough terrain spring pressure was increased from 41 to 62 kPa (6 to 9 lb/in^2). [8]

MOTOR

In making the motor selection we wanted the most reliable motor available. In keeping with our underlying design methodology, a DC motor will give more power per dollar then an AC motor. AC motor setups typically cost at least four times more than DC. NetGain Motors designs DC motors which are manufactured by Warfield Electric especially for the Electric Vehicle industry. We chose a NetGain WarP 7” motor (Figure 5). It has a 181 mm (7.125 in) diameter and is 425 mm (16.75 in) wide. Thus, it fits nicely on the width of the tunnel. It weighs 45.5 kg (100.5 lb) and delivers a continuous power of 15.47 kW (21.75 hp). Additionally, the motor has the largest shaft diameter of 28.575 mm (1.125 in) in this size case. The lamination size is 16% larger than a 203.2 mm (8 in) diameter motor. Advanced timing is easily set with pre-drilled holes. We did advance time the motor to gain about 2 % efficiency.

The motor also exceeds “H” class insulation and can do 7 200 rev/min at 120 V and 400 A for five minutes. With our emphasis for the design to be the best at the 32 km/h (20 mi/h) range event, the motor will produce 47 N·m (35 lb-f) of torque, and 2 100 rev/min using 48 V and 230 A. We performed the multiplication of the voltage and the amperage to arrive at a power of 11 kW for this motor at that setting. This produces a mechanical power of 8.9 kW and is a sufficient amount of power for the range event based on the last two years of the Clean Snowmobile Challenge results.

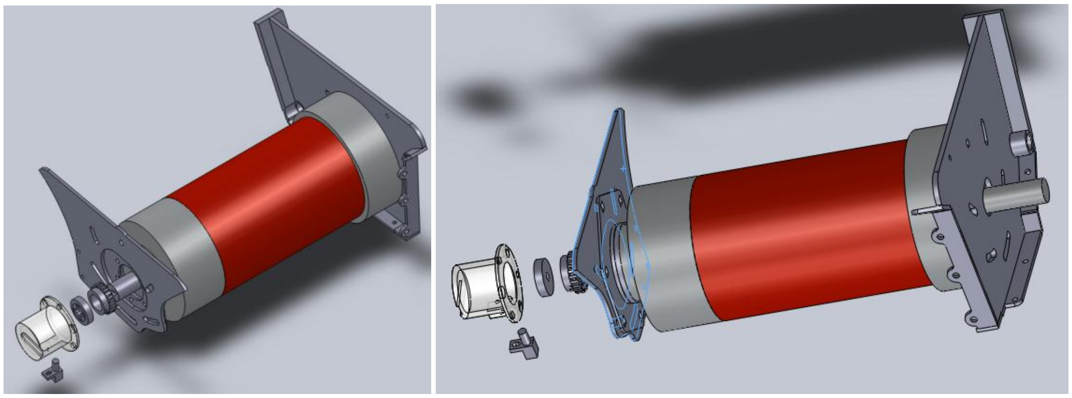

Figure 7: Solidworks rendering of WarP7 with motor mounts.

MOTOR MOUNT

One obvious component deletion was the internal combustion engine. This deletion created a major design challenge: to develop an electric motor integration system. The mount is constructed from 6061-T6 aluminum for long term durability -- as well as for its availability -- which is important to practicality and reproducibility. In order to produce a design for the mount, we had to determine the loads that the motor would produce. We accomplished this by examining the targeted performance for the snowmobile, and using those targets to identify the forces to be developed by the motor. After including the weight of the motor itself and doing an analysis for impact loading caused by bumps in the trail, we then included a safety factor, and were able to find the expected loads on the motor mount using static analysis. Once this was done, we were able to go about designing the mount. Each component must be able to safely handle both the weight of the motor and the drive forces that the motor produces. In order to ensure that each component is up to the task, the Finite Element Analysis suite COSMOS (which includes the design program SolidWorks) was utilized. With this program, the stress distributions within the parts and with the expected loads could be calculated. Due to the accelerated timeline of the project, these results were only used to ensure that an adequate safety factor was present. Costs were kept low by keeping precision machining to a minimum. When mating the motor to the chassis, modifications of the snowmobile were kept to a minimum. Existing bolt holes were used when possible. The design allows for a very strong, easy to use, and low cost solution to integrating the electric motor into the snowmobile.

BATTERY SELECTION

The snowmobile uses an energy storage system consisting of 72 Turnigy lithium-ion polymer batteries. These batteries were designed for high “C-rate” RC applications. Each battery is 5 A·h, and can allow 100 A·h drain. Our pack consists of eight batteries in a series connection to produce 177.6 V and 5 A·h. Then nine of these strings are paralleled together making a total 177.6 V and 45 A·h. This pack is capable of producing a continuous 160 kW at 20 C-Rate. We selected these cells because their rapid discharge rates were five times as high as the Headway 38120 cells utilized in 2010. LiPoly batteries were also chosen due to their reasonable cost and weight. These batteries allow 1500 cycles when discharged at 80 % in each cycle. After extensive battery research, we decided to use the cells manufactured by Turnigy. They were affordable and had a 40 % increase in mass energy density. There are currently many manufacturers of lithium batteries so our decision was extremely difficult and time intensive as we weighed our options.

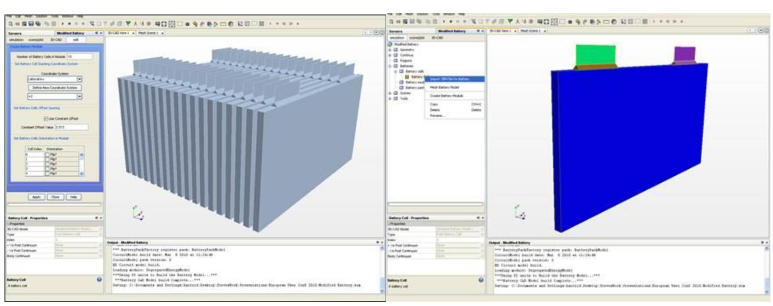

Figure 8: Battery Design Studio renderings of future battery designs showing the teams preference for prismatic cells.

BATTERY CHARGER

The team selected an Elcon CE-listed battery charger. This 2.5 kW model can charger the pack in 6 h at 110 VAC or 4 h with 230 VAC. Over 88 % of power taken from the grid is converted to real power to charge the battery. The intelligent microprocessor controller has optimized charge algorithms setup to charge different battery chemistries. We selected an algorithm that would work with our Lithium-ion batteries. Utilizing the correct algorithms helps improve battery life and minimize maintenance. Its rugged, lightweight and intelligent design provides continuous operation in any application.

ENERGY EFFICIENCY

To evaluate the efficiency of the Nanook EV, a comparison analysis with a standard production snowmobile was used. Assuming the best mileage a production IC snowmobile gets is 12.325 km/L (29 mi/gal), driving 46.67 km (29 mi) uses about 114 000 Btu of fossil fuel. This translates to 114 000 Btu / 46.67 km, which is 2 443 Btu of fossil fuels per km. The electric snowmobile averaged 250 W·h/km (400 W·h/mi) total energy use, which includes charging the batteries. Converting to British thermal units by multiplying 0.25 kW·h/km with 3 412 Btu/kW·h to obtain 853 Btu/km. Looking at how the electricity is generated will give a more accurate Btu comparison value, unless the sled can be recharged using alternative energy such as wind or solar power.

The worst-case scenario would be electricity from a coal fired power plant with an efficiency of 33 %. The fossil fuel input is 3 times the electrical power output, i.e. 3 x 853 Btu/km = 2 559 Btu/km. This number shows that an electric snowmobile is slightly less efficient than a production gasoline snowmobile. However, if a more efficient power generation is used such as a 45 % efficient power plant, then 2.22 x 853 Btu/km = 1 893 Btu/km which is less than the original gasoline consumption. The fact that a typical electric vehicle still has a significantly shorter range demonstrates the large discrepancy in energy density from a gasoline-powered sled to an electric sled.

Also, it is interesting to point out that even if the energy consumption is the same in either using gasoline or electricity to power a snowmobile, there are additional energy needs in order to bring that energy to a gas tank or a wall outlet. Argonne National Laboratory's The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model [11] can do a Fuel Cycle analysis, also known as "Well to Wheel" (or with snowmobiles "Well to Track.") (Figure 11).

This modeling software allows researchers to evaluate various vehicle and fuel combinations on a full fuel-cycle/vehicle-cycle basis. We used this modeling software to compare snowmobile combustion vs. electric snowmobiles. We estimated that an electric snowmobile operated with an 11 % reduction in CO_2 emissions and a 10 % reduction in Greenhouse Gases (GHG) based on energy generation in Fairbanks, AK [12]. The software will also give you modeling data on other emissions as well.

RANGE

For the past four challenges we have focused more on the range event than anything else. With the recent energy storage restriction has become harder to justify this focus. So for a vehicle to be practical it must be able to transport people and cargo over a usable range. There were many design decisions made to reach this goal. We didn't achieve our goals in 2009 since we expected to travel another 50 % further. What we didn't anticipate were extreme wet snow conditions. We have classified snow into three categories as shown in Table 4: Slush, Ice and Powder [12, 13]. Using data from the last three years of the CSC and Auth's Thesis [14] we calculated a rolling resistance coefficient. We also show our range estimation for our current sled depending on conditions. More information about calculating **rr** is in a previous design paper [10].

Table 4: Rolling Resistance Effect on Range

Snow Condition	Rolling Resistance [rr]	Distance	
		km	mi
Slush	0.377	39.2	23.5
Ice	0.252	55.4	33.3
Powder	0.15	83.8	50.3

RANGE TEST

The snowmobile was driven on a 1.33 kilometer (0.83 mile) track for range testing. The sled was driven at a constant speed of 32 km/h (20 mi/h). We kept the speed constant to maintain zero acceleration as much as possible. We ran the machine until the BMS alerted us that the machine needed to be recharged. We obtained 30 km (18 mi) on hard-pack snow, which we calculated to be 266 W·h/km by dividing 7.992 kW·h and the 30 km. This exceeds the old 16 kilometer (10 mile) standard which is still listed as a design criterion in the Clean Snowmobile Challenge rules, and this range can be exceeded or reduced with different snow conditions. [1] Knowing this, we tested again on a warmer day and ran the sled out on a river's surface; we were able to drive 20 km (12.42 mi) before receiving the BMS warning. This was calculated to be 400 kW·h/km. This amount is much higher than the power draw we saw in the first test, and shows the large amount of variability that exists due to snow conditions.

DRAWBAR PULL TEST

The drawbar pull is an interesting event in that many of the qualities that lead to drawbar pull success can be detrimental to performance in other events. Chief among these qualities is weight. A heavy snowmobile will achieve lot of traction, and thus be able to pull more. On the other hand, that weight is cumbersome in events like the range and acceleration tests. Judging from real-world experience, it was apparent that the limiting factor in the event would not be power, but traction. We may use studs to increase performance depending on course conditions. To test the snowmobile's performance in the drawbar pull, the back end of the snowmobile was attached to the back end of a parked truck with a two sets of triple blocks and a fish scale. The highest measured force was recorded. During testing, the maximum recorded force pulled against was 2.6 kN (590 lbf) At this point, the track lost traction and began to spin out. The consistency of the snow at the test site was a loosely packed, dry powder. Loss of power was not a limiting factor during the test. Maximum pulling force can easily be improved with a different snow consistency.

NOISE

The overall sound output of the machine was found to be quite minimal. We experimented with different tracks from Camoplast and Kimpex and on light powder the sled was performing below 60 dB. To address subjective sound quality, the motor used this year has an internal fan which is much quieter. Using the Poly Chain and the Silent Track technology has lowered our sound output. This 137 inch silent track (Ski-Doo part number 504152755) is a Camoplast track with added rubber to where the wheels meet the track. Since this is newer technology we thought it would also be considered an innovative in keeping sound levels low. An added benefit of this track is that it is narrower than the stock Renegade track that our machine came with, as well as having a 1" lug height instead of 1.25. Weighing the two tracks, we found that the new silentrack weight 38 lbs, while the stock track weighed 50. This reduction in rotating mass will help to increase our efficiency and range.

SUBJECTIVE HANDLING

The additional weight added to the snowmobile resides in the engine compartment. This allows for a low center of mass that the team wanted. The sled responds instantly to throttle input, a benefit associated with electric motors. Increases in speed can be made smoothly and quickly without the hesitation or 'jerking' often attributed to CVT clutches found in a traditional snowmachines. The sled is geared primarily for range by running the motor at its optimum rev/min while turning the track at a speed of 32 km/h (20 mi/h). As a result it can't pull the skis off the ground during rapid accelerations on flat ground, but it will easily stand up if the throttle is applied in any amount of deep snow.

<u>BRAKING</u>

The machine still employs the stock hydraulic disk brake system mounted on the paddle drive. In preliminary acceleration tests, where quick emergency style braking was required, the brakes showed little or no sign of fade. The stock rotor never showed signs of excessive heat buildup. This is attributed to the excellent job that BRP did when they designed the braking system, which is cooled directly by snow thrown up from the track.

<u>BALANCE</u>

The snowmobile is well-balanced front to back and side to side. Since the gas engine and clutches were spatially replaced with a motor and battery pack that weighs more, the weight over the front skis is greater than the stock values. This allows for better steering of the snowmobile. We have learned from previous competitions that having too much weight over the track was not helpful in the subjective handling test. As weighed on a pair of bathroom scales, there was no difference in weight between the left and right sides.

OVERALL HANDLING

The snowmobile exhibits a high overall level of comfort and performance. The seat is slightly elevated to simulate the popular high-rise aftermarket seats, decreasing the angle of the rider's knee and thus reducing joint and leg fatigue. The gauges are located in the stock locations, which still permits easy visual access. The original cable style throttle block was retained, and is more common on traditional snowmobiles. While the power was reduced and the weight was increased, the sled is still enjoyable to ride. It is by no means bulky or sluggish as many would envision an electric snowmobile to be. Aesthetically, it still retains its performance oriented styling and stance. Although some snowmobiles are used in commercial or research applications, the majority of the market is driven by recreational consumers. With this in mind we feel it is important that our final result still retained its original ability to provide a fun and comfortable ride, which the Nanook EV3 surely does.

WEIGHT

Adding the published dry weight with necessary fluids gives a wet weight of 232 kg (512 lb). The Nanook EV3 tips the scales at 250 kg (550 lb). The net weight increase is a mere 18 kg (38 lb). This new weight allows our machine to be competitive with many four-stroke gasoline powered snowmobiles available. The team did some weight calculations to determine how weight affects range. It appears about 27 kg (50 lb) can reduce range by 3 km [10]. We weren't happy with the battery pack energy storage capacity, but it may prove to be an adequate compromise. In the future the team will use more exotic materials to lighten the sled, and attempt to find a lighter battery pack with even higher energy density.

ACCELERATION

The acceleration rate is very challenging for an electric snowmobile. The high power demands of the event require high electrical currents being fed to the motor (upwards of 600 amps), and the large forces involved push the mechanical components to their limit. As with the drawbar pull event, traction is a major concern, though not as critical. The most important aspect of optimization for this performance is adequate motor sizing and gear selection. If the motor is too small, then the snowmobile will not be able to meet the minimum performance criteria for enthusiasts. If the motor is too large, the snowmobile may do well in the acceleration event, but the excessive loads that it places on the electrical system will hurt its performance in the distance event and harm its long-term durability. We believe the motor we selected, at 15.47 kW (21.75 hp), is the perfect size to provide both versatility and performance.

OBJECTIVE HANDLING

We tested the sled with this weight, and found no issues so far. We let our riders do several practice runs since this event will rely greatly on driver skill and experience.

COST

One advantage in working on a limited budget during this project is that our Manufacturer's Suggested Retail Price (MSRP) is extremely low. We went with a brushed DC motor to save $ 3 000 off the final price. We used lithium polymer batteries to save another $ 2 000. However, using Gates Poly Chain increased our cost by $ 700.

This $ 4 300 in savings should make us competitive against other teams, and make more researchers interested in acquiring a machine. Recent commercial snowmobile pricing has been on the rise for the last several years. This makes most chassis used in 2011 prohibitively expensive to convert to electric. We are thankful that the rules allow for a credit on the original motor; however this is not a realistic idea if you were planning a conversion business. Unfortunately none of the four major snowmobile manufacturers have taken an interest in a commercial electric sled. We realize there are major shortcomings in electric snowmobiles for certain user groups. However, a recent start-up company named Premier Recreational Products and other overseas vendors have developed a gasoline powered family-sled for under $ 4 000 [18]. Even though it is a smaller "three-quarter" sled, the 96 inch track would be usable in many situations. Using a chassis like this in a conversion would have an instant weight savings, and would be less expensive overall to convert. However, the Ski-Doo MX Z is so well engineered that C3 Power Sports has made a complete carbon fiber chassis. The excessive cost is high, but could afford an extra 10 km (6.1 mi) in range..

2012 SPECIFIC INNOVATIONS

The largest innovation this year was to use the RevXP as our base sled. The sled is very complex and has limited working room inside, making it very difficult to convert to electric power. Additionally, one design requirement was that the machine must look as close to stock as possible, with no hood modifications of any kind. Everything must be contained within the given working space.

A major innovation was the use of LED forward lighting that exceeded the previous light output, but decreased wattage consumption. The headlamps previously used 65 watt halogen bulbs and now use 10 watt LEDs. Saving 110 watts and based on 250 wh/mi drive train consumption using these lights will improve range by 33%. By disassembling the headlamp housings we were able to mount the LEDs internally and preserve the look and aerodynamics of the factory design. The rear tail light and brake light were also converted to an LED array for the same purpose.

For our display we used a small LCD screen mounted inside the originally instrument cluster. Having an LCD screen allows us to display many important variables like pack voltage and current draw. Buttons were mounted next to the screen to allow access to the BMS menus and spaced far enough apart for easy operation with gloves on. Large bright LED indicators were mounted in the same location to display the status of the snowmobile. We kept all the display components consolidated in the factory location to make it easier for the user and to preserve the look of the snowmobile.

It was also important to spend a lot of time on the design of the wiring harness, mapping out each wire and its function before assembling the machine. Having a master wiring schematic allowed us to design all the components to be removable by using high quality Deutsch and TE connectors. Making each component individually removable makes assembly of the sled much faster and easier. The entire wiring schematic is color coded to make electrical troubleshooting much easier as well.

Another innovative idea was the use of a 12 V accessory plug mounted externally on the snowmobile. The snowmobile's BMS and ignition system runs off the smaller 12 V battery. The smaller 12 V battery relies on the main battery pack to stay charged, but also powers the ignition relays. If the small 12 V battery becomes depleted, we can jump-start the ignition relays or charge the 12 V battery without removing the hood and accessing the 12 V battery directly. This 12 V outlet can also be used to power an accessory that is needed when another power source is unavailable.

PREVIOUS CHALLENGE RESULTS

The track conditions in 2010 were very poor, and we did some quick analysis that showed that we had better data in 2009. During the 2009 Clean Snowmobile Challenge, the Nanook EV performed admirably. All components performed as designed, and in some instances performed better than expected.

The first test in the competition was the range event. As range was a major focus for the design of the original Nanook EV, this test was critical to validate many of the design choices. During the test, the snowmobile was able to cover 27.6 km (16.6 mi). This distance was shorter than the anticipated range; however, it was still within the range simulations. Given the fact that the conditions during the test were not ideal and that all the other teams saw reduced performance compared to previous years, it is reasonable to assume that the reduced range was a result of the conditions, not problems with the vehicles' systems. The Nanook EV's performance in the range test was the best in the competition. The next farthest range was achieved by the UWM team with 20 kilometers (12.4 miles).

During the draw-bar pull test, the Nanook EV was capable of pulling against a force of 2.437 kN (548 lbf). This was much larger than the predicted result. We believe that our load cell used for measuring during initial testing may have been faulty. Our performance earned second place, behind UWM's result of 2.557 kN (575 lbf). This result is excellent considering the fact that the Nanook EV was not equipped with studs, which would have greatly increased traction in the competition conditions.

In the objective handling event, the Nanook EV was able to place second despite lesser acceleration performance than some of the other sleds. This was largely due a combination of the well tuned suspension, easy handling characteristics, and high performance skis.

In addition to these competition highlights, the Nanook EV was also the least expensive snowmobile present. This was great validation of the design, considering that cost effectiveness and maximum range were the two primary design goals, and also the two events we won. The Nanook EV finished second overall in the competition, a great performance for a rookie team.

SUMMARY

Having completed testing and competition with the Nanook EV 1, 2 and 3, it is clear that the design goals were met. We had a successful 2009 season, an interesting rebuilding years in 2010-11, and with our current testing, we feel confident of success in March 2012. A zero emissions snowmobile that is capable of excelling in the areas of range, pulling power, noise, handling, and weight has been produced once again, and this machine can have a broad range of uses outside the scientific research market. The Nanook EV3 is a low-cost, durable, easily reproducible snowmobile that is a pleasure to ride. We believe we have developed a breakthrough product that will address some of the criticisms of electric snowmobiles.

REFERENCES

1. 2012 SAE Clean Snowmobile Challenge Rules. Accessed online at http://www.sae.org/domains/students/competitions/snowmobile/rules/rules2012.pdf 25 Feb 2012
2. Wies, R. W., A. N. Agrawal, and R. A. Johnson, Hybrid Electric Power Systems: Modeling, Optimization, and Control, VDM Verlag, 2007.
3. Golub, M., Electric Vehicles in the Arctic, global glimpses, Accessed online at http://www.cgc.uaf.edu/newsletter/gg16_1/gg_Dec_2009 25 Feb 2012
4. Kordesch, K., 1977. Batteries, Volume 2, Lead-Acid Batteries and Electric Vehicles: Marcel Dekker
5. Hadi, S, "Synthesis and Characterization of Lithium Iron Phosphorus Oxide Cathode for Lithium-Ion Batteries," Thesis, University of Toronto, 2005
6. Lithium polymer battery information. Accessed online at http://www.rchelicopterfun.com/rc-lipo-batteries.html 25 Feb 2012
7. Lietman, S. 2008. Build Your Own Electric Vehicle: Tab Books
8. Brunka, T., email, Helwig-Carbon
9. Gates Design Flex Pro software Accessed online at http://www.gates.com/designiq/ 25 Feb 2012
10. Golub, M., et al., "Design and Construction of an Affordable Zero-Emissions Snowmobile," CSC Tech Paper (Fairbanks) 2009.
11. Brodsky, E., et al., "Refinement of a High-Efficiency Electric Drivetrain for a Zero-Emissions Snowmobile," CSC Tech Paper (Wisconsin) 2009.
12. Argonne National Laboratory, Transportation Technology R&D Center, Accessed online at http://greet.es.anl.gov/ 25 Feb 2012
13. US DOA, Rural Utilities Service, Operating Report, Golden Valley Electric Association, December 2006.
14. The International Classification for Seasonal Snow on the Ground. Accessed online at http://www.crrel.usace.army.mil/library/booksnongovernment/Seasonal_Snow.pdf 25 Feb 2012
15. Hansen G, "SnoLectric Electric Snowmobile Demonstration Status Report", 21 Aug 2001, Accessed online at http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CCIQFjAA&url=http%3A%2F%2Fdeq.mt.gov%2FCleanSnowmobile%2Fsolutions%2Fengine%2Fpdf%2Fhansen.pdf&ei=mFdJT9_SNISYiALTwZTbDQ&usg=AFQjCNH_86cMumSOsMviTN_9XgZDaeaHPw&sig2=osnXh3DXfEN-JNqd1VzorA 25 Feb 2012.
16. Auth, "Determining Hybrid Electric Snowmobile Feasability Through Simulation", M.S. Thesis, 2002.
17. Larminie, J. and J. Lowry, 2003. Electric Vehicle Technology Explained: John Wiley & Sons Ltd.
18. Premiere Enforcer 300 specifications. Accessed online at http://www.premierrpc.com/Premier_home_page.php 17 Feb 2010.
19. Open ReVolt Controller, http://ecomodder.com/wiki/index.php/Open_ReVolt

CONTACT INFORMATION

Michael Golub, migolub@alaska.edu, 907-347-4363

ACKNOWLEDGMENTS

Flint Hills Resources, UAF Alumni Association, UAF Technology Board, SBE Inc., Alaska EPSCoR, UAF Sustainability Fee, C3 Power Sports, Compeau's ski doo Wilderness Ski-Doo, Gigavac, Thermik, Peter Perkins, Paul Holmes, Gates, Tri Star Industries, Epoxies,etc, TE connectivity, Panduit, Deutsch Group, Maxim, 2 Cool Air Vents, Institute of Northern Engineering, College of Engineering and Mines, Lynden Transport, ASUAF, Walmart, Holland America, Conoco Philips, John Deere Learn Twice, Synlube, Northern Power Sports, Alaska Fun Center, Net Gain Motors, Worldwide Bearings, Helwig Carbon, University Alaska Fairbanks Provost's Office, U.S. Fish and Wildlife Service, Logisystems Controllers, NetGain Motors, ASME Northern Alaska Subsection, Kimpex, HMK, World Wide Bearings, National Science Foundation, Solidworks, AVL, Gates, Spangs Fab, Fairbanks City Bed-Tax, Usibelli Foundation, Curtis

APPENDIX

Here are the wiring schematics as required in the 2012 Clean Snowmobile Rules.