

The McGill Electric Snowmobile

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ABSTRACT

McGill University's new electric snowmobile aimed for a low cost and high performance solution for the zero-emission market. The highly customizable motor-controller system combined with extensive testing on an electric dynamometer permits user-specific power-limiting settings. Currently equipped with a National Instruments data-acquisition system capable of CAN communication with batteries, motor, and controller, the snowmobile's recorded data will provide a deeper understanding of the components.

INTRODUCTION

Every year, there are more applications found for the electric snowmobile. With a high demand in clean vehicle technology and large grants in battery research and production, range and cost are both aspects of the electric snowmobile that continuously sees improvements.

Other than a zero-emission means of transportation for researchers in Greenland, the great success the McGill electric snowmobile has demonstrated at the 2010 Vancouver Olympics in Whistler is a great example of a new application. The snowmobile towed children on a sleigh from the Children's Learning Centre to their lessons' meeting point. The touring market has even begun planning short trips, or eco-tours, on electric snowmobiles. Such tours would also be perfect for first-time snowmobilers because there is no intimidating engine noise.

The 2011 McGill electric snowmobile, based on a 2006 Ski-Doo Skandic, offers a more powerful and versatile snowmobile to the zero-emission market.

DESIGN OVERVIEW

DESIGN GOALS – For 2011, the McGill Electric Snowmobile Team (MEST) opted once again for a low cost solution but wanted significantly higher power available to the driver.

The first step in the design process is to understand the customer requirements. In this case, the competition

point scheme for the zero-emissions category represents these requirements. The actual design directly impacts the performance of the sled in the following events:

Table 1: CSC-ZE 2011 – Points Allocation

Manufacturer's Suggested Retail Price (MSRP)	50
Weight	100
Range	100
Draw Bar Pull	100
Acceleration + Load	50
Objective Handling and Drivability	50
Subjective Handling	50
No-Maintenance Bonus	100
Total <i>Design</i> Points	600

All of the events mentioned above are directly affected by design choices. From the scoring scheme, the following factors were the principal elements considered to set MEST's goals for 2011:

MSRP - Over the years, McGill has always made an extra effort to perform well in the MSRP event. Although it is only worth 50 points, one of MEST's design philosophies is to be as market-ready as possible. The cost of a conversion is already a substantial amount therefore to keep potential buyers interested, it is imperative to keep the cost low. The main technique employed is to keep as many stock components as possible while limiting body modifications to a minimum. To ensure design choices were valuable ones, the MEST performed a value engineering analysis on the drivetrain. More details on this analysis in the drivetrain section.

Performance – Out of the 600 design points, 250 rely on the sled's dynamic performance. Early on in the design stage, it was determined that performance was an area which had a lot of room for improvement in 2011. Here, the goals were to increase the power output from the previous year's system and have simulations provide the

optimal gearing ratio to balance low-end torque and top speed. The motor and controller combinations were tested on an electric dynamometer. The simulation program used was Powertrain Simulation Analysis Toolkit (PSAT).

Weight – Having the lightest snowmobile in the zero-emissions category rewards 100 points. Although being too light can limit the snowmobile's available traction, the lighter snowmobile is easier to move around, therefore is less demanding from the energy point of view. This was achieved by choosing a lightweight snowmobile, a 2006 Bombardier Skandic. Weighing in at just 375 pounds before conversion, it is a good base to build a lightweight electric sled.

Other – Reliability and practicality were two additional aspects given high design importance. From the scoring scheme, the 100 points allocated as a no-maintenance bonus falls directly in this category. Earning these points can make the difference to determine a winner. For a commercialized product, reliability is also of upmost importance. To learn more about the reliability of the new prototype, a National Instruments data-acquisition system was installed to record and monitor several on-board sensors. In terms of practicality, the main component that falls under this category is the on-board charger. Again, keeping marketability in mind, having an on-board charger is essential even if it increases cost and weight.

POWERTRAIN – The 2011 sled is equipped with the following key powertrain components:

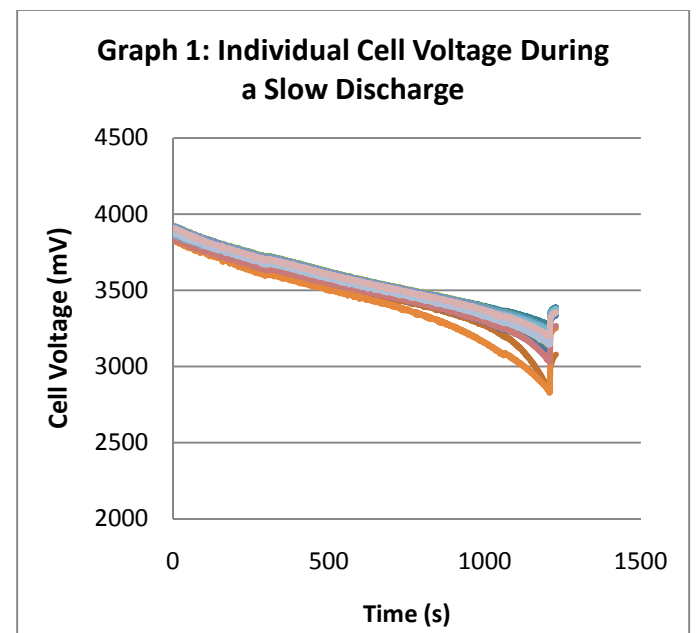
Table 2: Powertrain Component Selection

Batteries	LTC, 3.24 kWh, 72 V
Motor	HPEV AC-15, 25 kW
Controller	Curtis 1238, 550 A

Conversion summary – The batteries and AC induction motor were tightly fitted inside the original engine compartment. The motor controller and data acquisition system were placed inside a box under the seat, replacing the fuel tank. Under the front body panel, a large electronics box which contains contactors, fuses, and charger is fixed to the chassis. The remaining space is used to channel high voltage wires from the various enclosures in liquid-tight type A non-metallic conduit. This conduit is not required per competition rules but it is a valuable additional safety feature.

Energy storage system – The cost of converting an IC snowmobile into an electric one is largely determined by the battery pack. The MEST feels that investing in fewer high quality cells as opposed to more lower quality, less expensive cells is the best design choice. The higher quality cells will have a longer life and therefore reduce the cost on the long run. The batteries chosen were

3.6V, 45 Ah cells by LTC. The battery pack consists of 20 of these cells in series for a nominal voltage of 72V and pack size of 3.24 kWh. Today, they are six years old and have endured harsh cycles. It can be observed that the snowmobile battery pack is not performing at the same level as before. However, after all these years of abuse, the pack remains very functional. CAN communication was used to examine all the cells and find the weaker ones. These cells were identified and replaced. Presently, CAN is constantly measuring the voltage, current, temperature and state of charge of each cell, therefore if there is a problem with any of the cells, it can be immediately discovered and action can be taken. The main criteria for establishing the quality of the cells is how well they hold the charge. The basic test is to charge the cells and not drain them. After some time, the state of charge of the cells would be measured. This is usually a very good indicator of the cell's healthiness. It is also possible to monitor the cells as they slowly discharge to simulate endurance runs and as they discharge very rapidly to replicate loaded acceleration runs. Below is a graph showing the voltage of each cell as the pack is drained, clearly indicating the weak cells.



This test allowed the MEST to identify two weak cells that needed to be replaced.

To improve performance in various events, the BMS was reprogrammed to allow a higher current flow. The previous limit was set at 200A. Due to the BMS parameter changes, the team could now gain access to the full potential the LTC cells have to offer. The limiting factor will no longer be battery power but rather the wire size choice which will determine the fuse size.

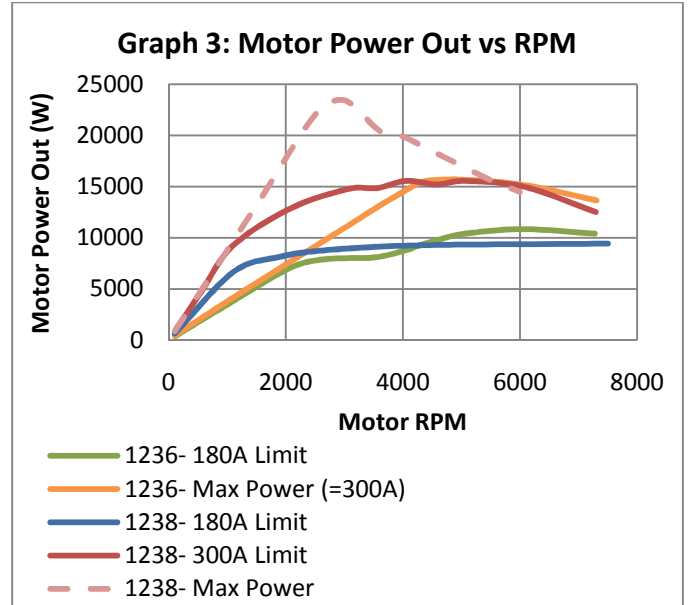
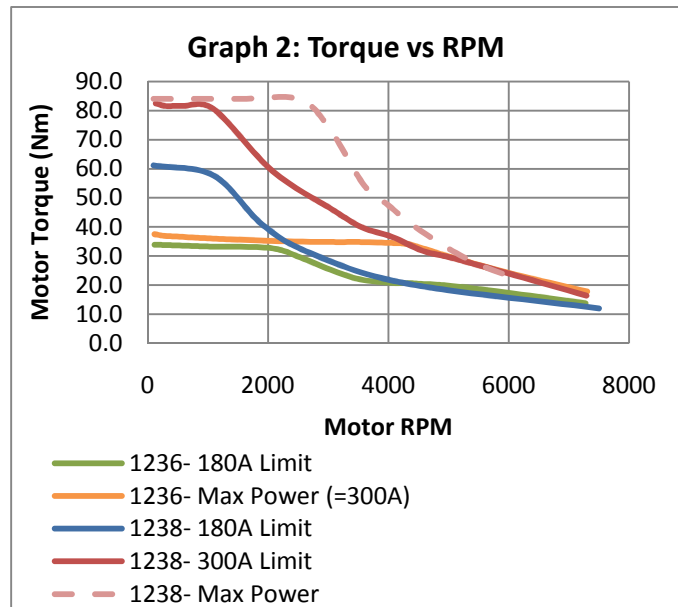
Motor and controller – The chosen motor and controller came as a package together for a total cost of \$3,200. The motor is an AC induction machine with maximum output of 25 kW. The motor controller is a Curtis Instruments 1238, with 48-80V range, which has a

maximum current output of 550 A_{rms}. This new controller increases the current limit of 300 A_{rms} on the previous prototype's Curtis Instruments 1236 controller. Although the change comes with an extra cost of \$600, extensive testing on an electric dynamometer and powertrain simulations proved this change to be a valuable one. Figure 1 below shows the electric dynamometer setup at McGill University.

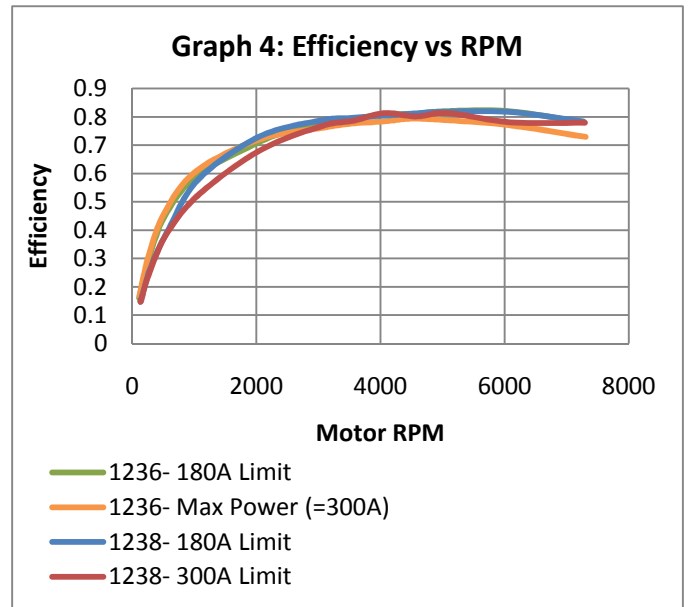
Figure 1: Electric Dynamometer Setup



Tests were performed to determine whether or not the new controller would be a good addition to the 2011 snowmobile. The experiment was carefully planned to ensure the best quality of sampled data as possible. The different curves represent different battery current limits. Battery current was chosen as the main experiment variable instead of motor current because it is more convenient. The 180A and 300A limits were specifically chosen because they correspond to gauge 2 and 2/0 wire fuse requirements. All tests were performed with the snowmobile's battery pack at 71 OCV. Between each sample point, the pack was recharged to the same level. The following three graphs present a comparison summary between the 1236 controller with the new 1238 controller.



The first point to notice from Graph 2 and 3 is that for torque maps of equivalent current limits, the motor output is only different in the lower rpm range until maximum power is reached. Also, if the 300A limit was set, the 1238 controller would provide more than twice as much torque as the 1236 controller at lower speeds.



In Graph 4, the efficiency measured is the controller and motor combination efficiency. It is calculated as follows:

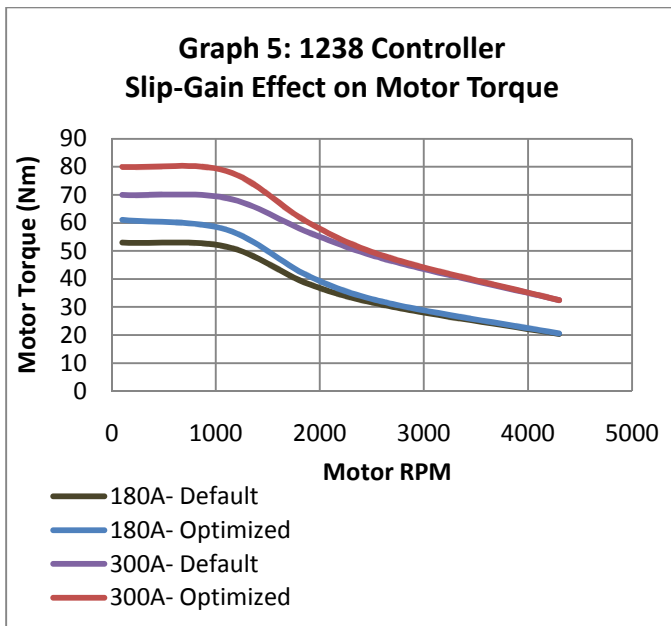
$$\eta = \frac{\text{Motor Power}_{out}}{\text{Battery Power}_{out}} = \frac{T \cdot \omega}{I \cdot V}$$

Where,

- T : Motor torque (Nm)
- ω : Angular speed (rad/s)
- I : Battery current
- V : Battery voltage

All setups give similar efficiencies except for the 300A limit on the 1238 controller which runs below average for lower rpms.

The Curtis Instruments motor controllers are highly customizable. For the different current limits tested, the controllers were fine-tuned by adjusting system parameters such as slip-gain, to maximize low-end torque. Maximizing low-end torque is a logical choice for an electric snowmobile because of the gains possible in the CSC scoring scheme and for towing heavy equipment on the Greenland Ice Cap. The following graph shows how much the torque curve varies with the slip-gain parameter for the 1238 controller.



For both current limit maps, peak torque has increased by approximately 15%. Not only is this increase substantial, it corresponds to an increase for about a 2000 rpm range.

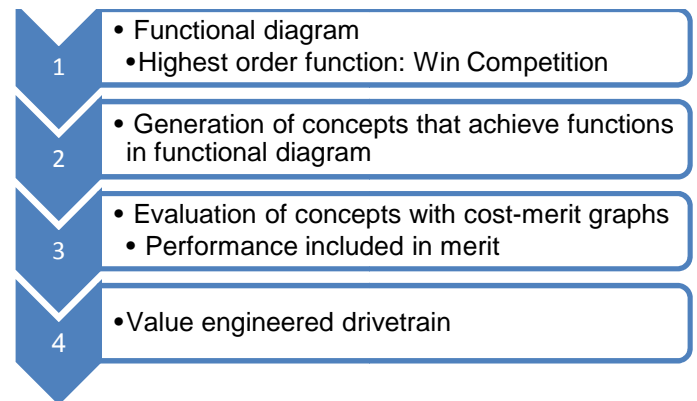
Draw bar pull – The draw bar pull event is won by the sled that can transmit as much force to the ground as possible. This indirectly implies that the higher the motor output torque the better the sled can perform. Looking back at all the data obtained on the electric dynamometer, the slip-gain optimized 1238 controller has a significant advantage over the previous prototype's 1236 controller which clearly makes it the better choice for that event. The same train of thought can also be applied for the loaded acceleration event.

Subjective and objective handling – The 2011 McGill sled will be much quicker off the start than the 2010 prototype which should therefore translate in quicker lap

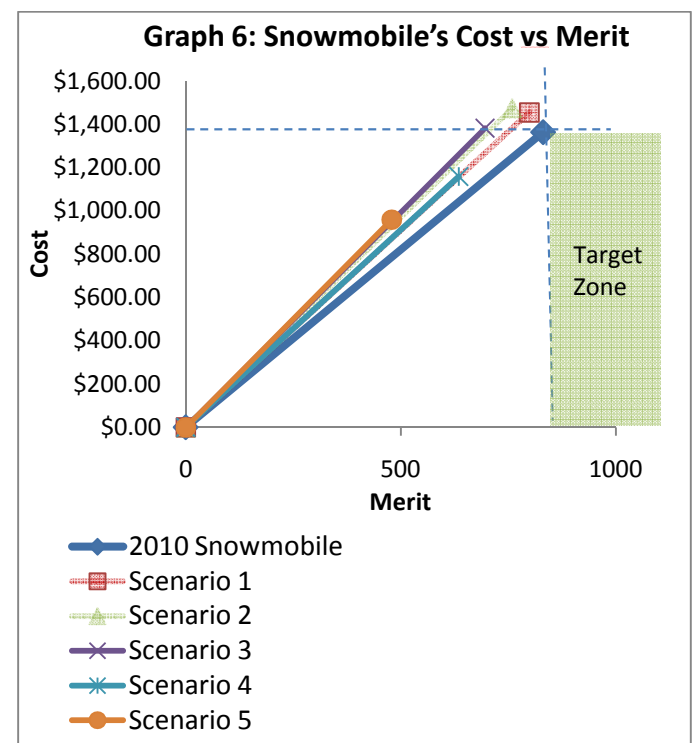
times in the objective handling event and will also be more exciting to drive at lower speeds, thus pleasing the avid snowmobiler and judges for the subjective handling event.

Drivetrain – During the first stages of the design process, the MEST performed a value engineering analysis on the drivetrain. For this exercise, drivetrain was defined as all mechanical components linking the motor output shaft to the track. The following flow chart depicts the main sections of the analysis.

Figure 2: Value Engineering Approach



Some of the concepts, also called scenarios, generated included custom gearboxes and CVT transmissions. In the end, it was determined that the design with the highest value was the 2010 drivetrain concept. All scenarios were compared to the 2010 design which consisted of a belt drive connected to a jackshaft, chaincase, and driveshaft. Graph 6 shows the analysis results:



The metric for evaluation were merit points. Merit points are a combination of predicted performance in each of the competition's events, ease of manufacturability, rotational inertia, and market value.

What this exercise produced was that the best drivetrain design was the one used on the 2010 sled. No other scenarios were both less costly and higher in merit. The decision was therefore made to keep the drivetrain concept unchanged. What could change however was the drive ratio.

After determining the general drivetrain design, the motor and controller performances were measured on an electric dynamometer. This ultimately indicated that the 1238 controller was far superior to the 1236 controller. The next step was to determine the final drive ratio. Using the dynamometer data, a snowmobile model was built into PSAT. To reach high levels of simulation accuracy, coast downs were done to determine what forces are acting against the snowmobile for every speed. The coast down data was then added to PSAT. The simulation objective was to determine the drive ratio that offers the best compromise between acceleration and efficiency at 32 km/h which corresponds to the endurance event speed. The simulations were setup as accelerations for four different distances. The results obtained represent the time required to reach these distances. The following table summarizes PSAT results for a 180A current limit on a 1238 controller:

Table 3: PSAT Acceleration Results - 1238

Drive ratio	2.65	3	4.35	4.94	5.29	6
25 m accel	4.1	3.9	3.7	3.7	3.7	3.7
50 m accel	6.4	6.2	6	6	6.1	6.3
100 m accel	10.4	10.2	10.2	10.5	10.7	11.3
152 m accel	14.4	14.2	14.4	15	15.4	16.4

To further emphasize the gains of upgrading to a 1238 controller, similar simulations were done with the 1236 controller for the same current limit. Table 4 summarizes the results.

Table 4: PSAT Acceleration Results – 1236

Drive ratio	3	4.35
25 m accel	6	5.1
50 m accel	8.9	7.7
100 m accel	13.6	12.1
152 m accel	18.1	16.3

The simulation results clearly demonstrate the difference between both controllers, especially for shorter acceleration runs.

Range – Before choosing the drive ratio, first the efficiency must be considered for the range event to determine whether or not a compromise has to be made between efficiency and performance. The MEST decided to use a smaller battery pack in the hope to earn more points in the MSRP and weight events. Nonetheless, from the efficiency graph, Graph 4, a peak efficiency range from 3000 to 6000 rpm can be extrapolated. Over this entire range, motor and controller efficiency hovers around the 80% mark. As long as the snowmobile can reach 32 km/h in this range, the distance travelled will be similar. Knowing this target rpm range, the 2.65 and 3 drive ratios can be eliminated from the list. From the four remaining ratios, the fastest accelerating one is the ratio of 4.35. Therefore, this ratio was chosen for the drivetrain. As an added bonus, at this ratio, 32 km/h corresponds to 4027 motor rpm which is approximately the peak efficiency point. Thus, the snowmobile's range at 32 km/h will be maximized.

The ten mile range requirement would definitely be met if the battery pack was assembled with new cells. Considering the cells have been through over five years of use, the ten mile range is not guaranteed to be achieved but everything was done to maximize it.

Ergonomics – An important aspect for many potential buyers is that the sled should not look or feel any different than an internal combustion sled. To accomplish this, the space beneath the body must be efficiently separated between electronics, batteries, motor, controller, and drivetrain in order to preserve the driver's position. Not only has this been achieved, but also without altering the structural integrity of the chassis. This means that the snowmobile ride comfort essentially remains the same after the conversion.

On the dash, a wireless GPS system will display speed, elevation, and distance travelled, customizable to the user's needs. An additional display will provide battery current, voltage, and temperature wirelessly from the on-board embedded controller.

A standard light switch is mounted on the controls panel alongside a forward-reverse switch. As a supplement, a siren switch is setup if ever the snowmobile must pass through crowded areas.

CONTROL AND DATA-ACQUISITION SYSTEM – The data-acquisition system used previously was an Isaac Instruments V7 Pro connected with various sensors for voltage, current, etc. The new system was designed to use a National Instruments Compact Reconfigurable I/O system (NI cRIO) in combination with several NI modules. The possibility of having the choice between several different modules for the cRIO allows it to be a very flexible system. It currently performs both control with output signals and data-acquisition of input signals from sensors placed throughout the snowmobile. The modules presently installed consist of a 32-channel analog input (NI 9205) to measure voltage signals; a 12-channel universal module (NI 9219) capable of

measuring input voltages, current, or resistance; a 4-channel analog output (NI 9263) to send voltage signals; and finally a 2-port high speed CAN bus module (NI 9853). This leaves 4 empty slots remaining to add additional modules as needed. The analog input module is wired to a voltage sensor and a current sensor, both attached to the battery pack while the universal module measures the throttle potentiometer's resistance value. By using the cRIO and programming the LabView software running on it, all the desired values are logged. Furthermore, it is possible to adjust the output motor controller signal from the throttle input. This would allow the throttle signal to be adjusted to provide better traction control and to increase the snowmobile's efficiency by limiting unnecessary power consumption. The possibility of programming this on-board computer to our needs contributes to the flexibility of this control & data-acquisition system. For now, only a simple control & data-acquisition system has been used (see Appendix – Figure 3).

The CAN module provides the ability to get different parts of the power train, the batteries and the motor controllers (prospective plans), to communicate with the cRIO using the CAN communication protocol. CAN bus is a standard protocol that has been used in the automotive industry for a fair amount of time; it is used to integrate different electronic parts of the vehicle with the central computer that controls and monitors each.

Having working reliable communication between BMS, the motor controller and the cRIO will allow the team to acquire more information directly from these systems. Furthermore, this would reduce the complexity of the whole system by reducing the number of sensors required. For example, the battery management system (BMS) already has information about voltages and current at each individual lithium-ion cell and for the whole battery pack, but in the past, additional voltage and current sensors were required to obtain these values. In the case of the motor controller, it was not possible to obtain any information about the electric motor. With CAN, crucial information may be collected such as motor rpm, motor and battery's voltage and current. This becomes useful for research and development of the snowmobile. Furthermore, having access to information such as battery pack temperature in real-time allows the system to react by issuing warnings to the user should any problem occur.

The strategy that the team used in this project is to investigate the working principle behind the CAN communication protocol and understand the general working of this protocol. The next step was to study the battery and the motor controller in terms of their capabilities in implementing the CAN protocol. This included a study of the devices' properties such as the type of CAN protocol that has to be used, the speed (baud rate) at which the data can be transmitted and the modifications to the actual hardware in order to establish connection between the hardware and the cRIO. Next, the team studied and understood the working principles

and the capabilities of the cRIO followed by an analysis and study of the software (LabView) that allows us to communicate with the cRIO.

The cost for the whole system breaks down to \$3,815 for the cRIO and \$3,910 for the 4 modules and a high-speed CAN cable required to connect the module to the BMS for a total cost of \$7,725.

This high cost is only associated with the current prototype since most of the equipment used here are development kits meant for rapid software prototyping. For a deployed model, a simple conversion to using an NI single-board reconfigurable I/O (NI sbRIO 9632) equipped with all necessary analog inputs/outputs along with universal (NI 9219E) and CAN modules (NI 9853) should cost about \$4,750 in total. This cost is an estimated cost based on the prices for a single purchase; one can assume that costs would be even lower should this kit be purchased in bulk. A more tailored solution could even be designed using a Xilinx or Altera FPGA board since both companies offer systems for automotive networking with support for CAN. An adapted solution such as this would greatly reduce the hardware costs.

OTHER FEATURES – To increase the sled's practicality, an on-board Delta-Q charger with integrated DC-DC converter was added. This charger is compatible for 120 or 220V inputs which means it requires no modifications if it were to go to Europe. Having an on-board charger gives much more freedom to the snowmobile. It does not need to return to the same place after every ride as long as an electrical outlet is available.

Maintenance costs associated with the snowmobile are close to null for the powertrain. The motor is brushless therefore requires essentially no maintenance.

Another handy feature on the snowmobile is its regenerative braking capability. This feature would be most useful for a snowmobile going downhill and using nothing but regenerative braking to slow down. The battery can handle pulse charge currents of up to 270A.

CONCLUSION

For 2011, the McGill electric snowmobile offers a low cost snowmobile customizable for several applications including Summit Station in Greenland. The new controller allows the user to access more power if ever necessary such as climbing steep hills or towing heavy equipment. Value engineering yielded an optimal, cost-efficient drivetrain design that was later refined through dynamometer testing and simulations to determine the final drive ratio. For added convenience, the sled is equipped with a charger that makes it a complete vehicle, ready for the real world.

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APPENDIX

Figure 3: Control & Data-Acquisition System Flowchart

