Modular and safe eSled expedition electric snowmobile

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ABSTRACT

The Lapland University of Applied Sciences (Lapland UAS) is participating the CSC ZE for the first time ever in 2015 competition. Lapland UAS's Arctic Power research and development unit has been researching zero emission snowmobiles since 2008. These earlier prototypes have been tested thoroughly and Arctic Power has even constructed a small fleet of four electric snowmobiles for Lapland Safaris, a company arranging snowmobile safaris in Rovaniemi. The snowmobile used in this challenge is a slight remake of our RD10 model based on a 2012 Lynx Adventure LX 600 ACE chassis.

INTRODUCTION

The CSC ZE 2015 competition encourages participating teams to innovate a practical zero emission snowmobile to be used to conduct research activities in remote areas. For example the United States government agency called the National Science Foundation (NSF) has a research location Summit Station in Greenland. The research NSF is conducting in the area is very sensitive to emissions resulting from the IC engines. Thus, a zero emission snowmobile for transportation between facilities would be ideal. The current evolution of battery technologies has made it possible to construct zero emission vehicles for limited range purposes. The most important requirements for the ZE snowmobile set by the NSF are range and draw performance.

Our team will address these requirements along with other features in this design paper. From our team's perspective, the ease of maintenance could also be a valuable aspect for the researches. Our design will also reflect consideration of modularity and safety.

DESIGN OBJECTIVES

Commercialization

One of our main objectives set by our funders was to create a product that is as ready as possible for a mass production. Therefore the commercialism is an important aspect for us. Attending the CSC gives us a wider understanding about the Northern American market requirements. With the experience gained we can take our project further and further and finally in the future create a product with a worldwide markets. Even a local sale would drastically accelerate the research and development.

Multiple component manufacturers

With our multiple component manufacturers we are not bind to a certain manufacturer. By this we achieve a better selection and we can change a part to another part manufactured by a different manufacturer with none or minor expenses.

Maintenance

One of our main objectives was to make a prototype that is easy to maintain and repair. Every device is reasonably accessible and none of the parts blocks the access to the other parts. Most of the removable parts have connectors for easier replacement.

CSC 2015 ZE specific design goals

Safety

The rules set by the SAE CSC forced us to rethink and renovate the safety systems already installed into the prototype. As the rules state the safety switches must carry the current directly. Earlier our switches were normally open which controlled normally closed relay. Our key switch controlled the relays. Now all the current used by the system except the power used by the last stage flows through the key switch. Last power stage includes the motor controller and the lights.

Tractive system includes multiple safety features as the high voltage interlocks and the high voltage disconnect. The batteries will never be connected while the tractive system is not fully set. Charging is covered by the same safety features.

We have also grounded our LV system to the snowmobile chassis and added an insulation monitoring device which is important safety device to detect a traction system insulation faults. Other traction system safety features include a master switch, insulation error latching, manual insulation measurement points, and the BMS.

Overall performance

Our team aimed for a reliable everyday sled. With our snowmobile's high modularity we can easily swap the ill-functioning components and obtain ever higher stability. In our current model the most of the parts used are tested in earlier prototypes and have proved themselves worthy. This might be one of our advantages in the competition.

Range

With our pre-CSC RD10 we have achieved an average of 238Wh/km (2.6 miles/kWh) (**Figure 1**). After the weight reduction and other CSC modifications the consumption should decrease.

With the 4.96kWh battery capacity installed we are hoping for a ranges over 20km (13 miles).

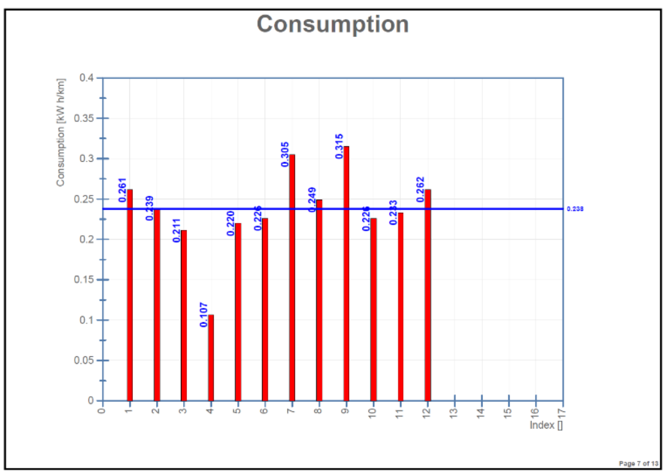

Figure 1. Consumption chart

Draw Bar pull

We have very little data of draw bar pull results. According to the motor force chart and the fact that our sled is a bit back-weighted we should do adequately. This is absolutely a part that will be improved later on.

Modularity

Interfaces

By opening the left side body panel user can easily connect to the configuration interfaces. Connections available are USB, CAN bus and RS-232. The USB interface is for the dash and the RS-232 is for the motor controller. Other devices are configured via CAN bus.

The interfaces are located behind the left side body panel, for the operator's convenience, because there is only one HV connection directly accessible and the accumulator indicator led is clearly visible. The brake is easily operable in an emergency situation and the interfaces are easy to access. While configuring, the dash and the dash leds can be seen as well.

Subassemblies

Most of the subassemblies are designed to be interchangeable with a compatible part. I.e. the dash can be replaced with any CAN bus dash, the battery container as a whole, battery charger, and motor controller and motor as a compatible pair. This enables us to improve the sled by updating the parts used or upgrading the system with a better alternative components.

Programmability

The snowmobile is equipped with a remote telemetry system that is python programmable. Along with the telemetry system we have installed a myRIO embedded system. Currently our system uses only the myRIO's FPGA processor. The myRIO has also a dual-core ARM processor which can be programmed with various languages. The dash, motor controller and BMS can be configured with programs provided by the manufacturers.

THE FIRST ESLED EXPEDITION

Chassis

The chassis selected for the sled is a 2012 Lynx Adventure LX 600 ACE touring snowmobile. The selection was based on availability as our team already had this chassis from earlier projects. The chassis also has subtle amount of space to place components freely. It is designed to be stable and easy to handle as it is a touring sled. The **Figure 2** shows 2011 model of the same snowmobile. The only visible difference to the chassis used in the CSC 2015 ZE is the rear bumper model and body painting.

Figure 2. Lynx Adventure 2011 LX 600 ACE chassis.

Modifications

Our team has switched the rear suspension from the PPS-3500 to the Ski-Doo SC-5. Both are stock components of Lynx Adventure models. The reason to this change is the lighter weight of the SC-5 rear suspension.

The rear A-arm has been modified (**Figure 3**) to make it possible to install the battery container on the tunnel. It was necessary to build new mounting points for the rear A-arm. These mounting points are located in the battery container support frame which is permanently installed to the front part of the tunnel.

Figure 3. Rear A-arm modification and mounting points.

Drivetrain

The drivetrain has been designed to use as much stock parts as possible to keep the costs at minimum. The stock parts we have left from the base sled are drive shaft, chain case, drive sprockets and drive chain. The chain case cover has been modified a bit to make it possible to attach the DC motor adapter to it. Also the upper drive sprocket has been modified in order to install the DC motor shaft directly to it.

DC motor

Our team has selected the LEM-200 D135 84V brushed DC motor to be the motor of the competition sled (**Figure 3**, lower right corner). One of the main reasons for the selection is that the motor has been in use in earlier projects as well and it has functioned reliably. There were also motor mounting adapters and test data available already. Other main reasons behind the selection were its light weight (11kg), reasonable size and high efficiency (up to 93%). The motor has a peak power of 29kW while the rated power is 16.84kW. The maximum RPM of the motor is 3780. The motor is designed to be used at constant current of 200A and it can withstand peak currents of 400A. While the low RPM torque is adequate, the low RPM power is a disadvantage of brushed DC motors.

DC motor adapter

It was required to design an adapter for the LEM-200 D135 DC motor to be fixed onto the chain case and to fix the motor's axle to the drivetrain. The **Figure 4** shows the adapter design drawing. The motor will be mounted to the 4 small holes around the recessed circle and the axle goes through the larger center hole.

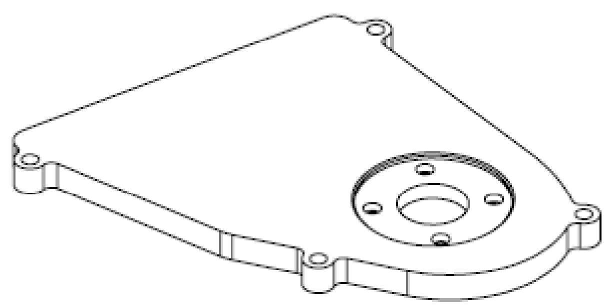

Figure 4. DC motor adapter drawing.

It was also required to modify the upper drive sprocket to connect with the DC motor's axle. Our team designed modifications seen in **Figure 5** to the upper sprocket as can be. The center hole of the sprocket was widened to fit the DC motor axle adapter making the DC motor connection to the drivetrain possible.

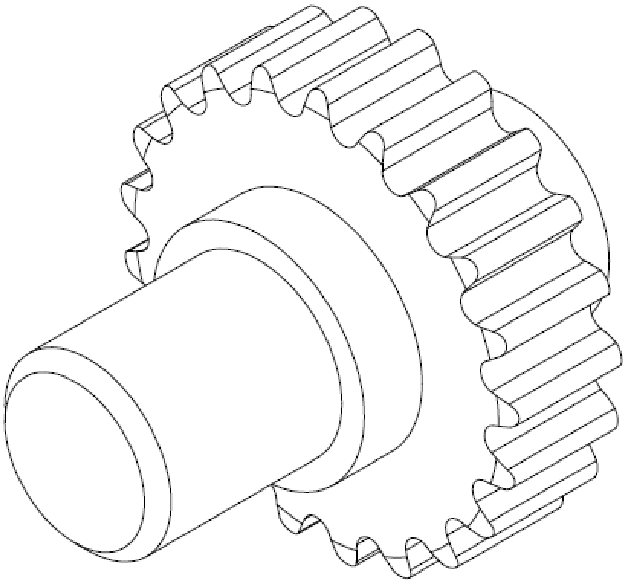

Figure 5. Modified upper drive sprocket with DC motor axle adapter.

Motor controller

The Kelly HPM14701C was selected to be the motor controller of the competition sled. It is a reasonably priced permanent magnet DC motor controller with high efficiency. This controller and its sister models have been tested in earlier projects and results show they are performing reliably. HPM14701C is rated to 315A at 144V and additionally it can handle 700A for one minute.

The motor controller is fully configurable, enabling our team to adjust the settings to reach design objectives. The controller continuously monitors operating conditions and triggers alarmed if error conditions occur. When alarm is triggered the power output will be shut down immediately.

Efficiency

The data in **Figure 6** shows how the efficiency of the drivetrain develops with the RPM. The drivetrain efficiency is best at the higher RPMs. The best overall efficiency can be achieved by choosing the gear ratio according to the performance needed. The gear ratio we have chosen is a compromise between the top speed and the startup torque.

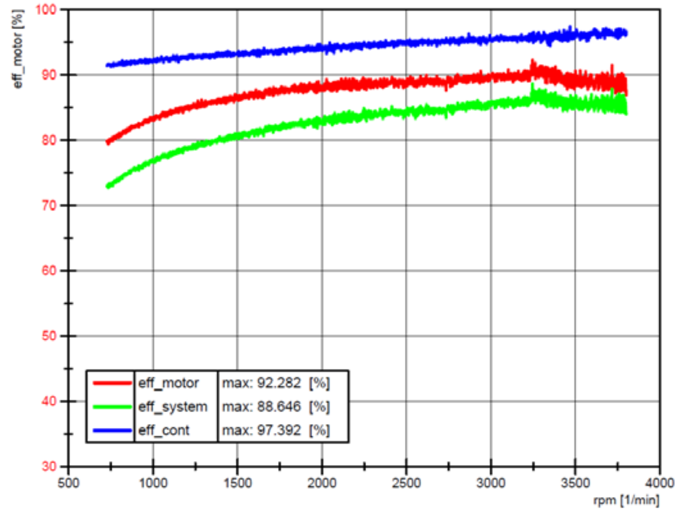

Figure 6. Typical efficiency data of LEM-200 135 DC motor with Kelly HPM14701 motor controller. Tests have been done using engine dynamometer. The graph shows combined results of four separate tests.

Batteries

The selection criteria for the batteries was defined to be following: commercially available, reliable, modular and well tested. Our team has selected U-Charge® U27-36XP 38.4V battery modules (**Figure 7**) from Valence Technology, Inc. for the competition sled. They are well known and widely used battery modules which have been in the market since 2006. The battery module dimensions are designed according to BCI group number 27. One battery module weights 19.6kg and has energy density of 91Wh/kg. The battery module is coated with flame retardant plastics.

Figure 7. Valence U-Charge® U27-36XP modules before installation to battery container.

Battery chemistry

The cell chemistry of Valence's IFR18650EC cells used in the U-Charge® U27-36XP battery module is lithium iron magnesium phosphate ($LiFeMgPO_4$) which is designed to maximize energy and safety while providing high cycle-life and performance. The battery module has a nominal voltage of 38.4V and capacity of 46Ah (C/5 @ 23˚C).

Battery pack configuration

A single U-Charge® U27-36XP battery module is configured as 12s33p. The battery pack of the sled is configured as 3s1p consisting of 3 U27-36XP modules in series. This accounts to total amount of 396 cells per module and 1188 cell per 3s1p battery pack. With this configuration we can reach 5.95 MJ of energy per module (C1 rate), totaling to 17.85 MJ for the whole battery pack which equals approximately 4.96 kWh. Nominal voltage of the battery pack is 115.2V and nominal capacity is 46Ah.

Our team had to make a tradeoff between the battery pack energy amount and number of modules because of our design choice of single battery container. We started designing with a total of 6 U27-36XP modules but we couldn't use all of them because of the 8kWh limitation declared in the rules. Optimum configuration would have been 3s2p but it would have totaled to about 9.92kWh. We also considered to use 2s2p but in that case the nominal voltage of 76.8 V wouldn't have been optimal for our 84V DC motor. Additionally, configuration of 4s1p was considered but it was found out that the nominal voltage of 153.6V was above specifications of our motor controller and BMS unit. Therefore it was quite straightforward choice to proceed with 3s1p configuration. This choice enables battery swapping as we can build two identical 3s1p battery packs.

Battery container

In addition to the guidelines set by the competition rules, our team has set its own design objectives for the battery container. Objectives were plug & play installation to the sled, battery swap possibility, modularity and safety.

The battery container walls and floor are built of 2mm thick aluminum. The container's lid is made of 3mm thick aluminum. The container has two separated segments, one for the batteries and one for the electronics. The segments are separated by a firewall made of 2mm aluminum. The batteries are fixed into the container using steel support frames made of 3mm thick 30mm wide steel plates. The electronics are fixed on a rugged 4mm aluminum plate. The container walls are covered with non-conductive 3mm thick rubber mat.

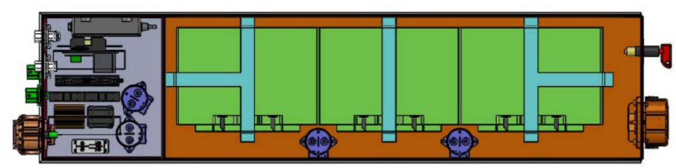

Figure 8. Top view of the battery container.

There are fixed mounting points installed for the battery container on the sled's tunnel. There are also guide bars installed on the tunnel to make it easier to push the battery container firmly in its place. The container is fixed to the sled by 3 steel U-rods. The foremost U-rod supporting the rear A-arm is a part of the snowmobile chassis and it is made of wider steel than the two other U-rods.

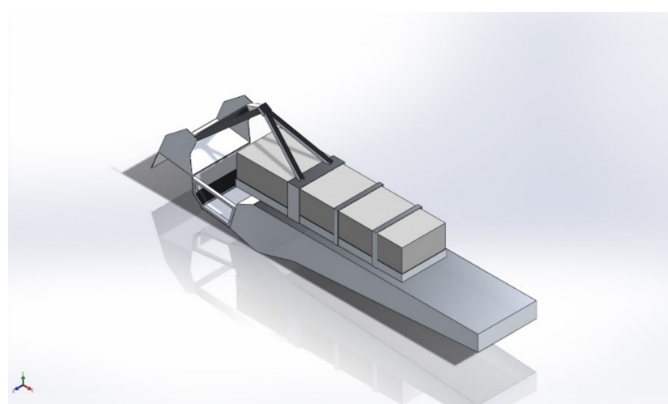

Figure 9. Battery pack mounted on the sled.

The battery container, container mounting, and chassis modifications have been simulated according to the SAE CSC rules using SolidWorks 2014 educational edition. The results show the container and rear A-arm are robust enough to withstand the 20G horizontal forces as can be seen in the **Figure 10** and **Figure 11**. The simulation figures show stress distribution in N/m^2 and the deformation scaling is set to 2500 to highlight the deforming areas.

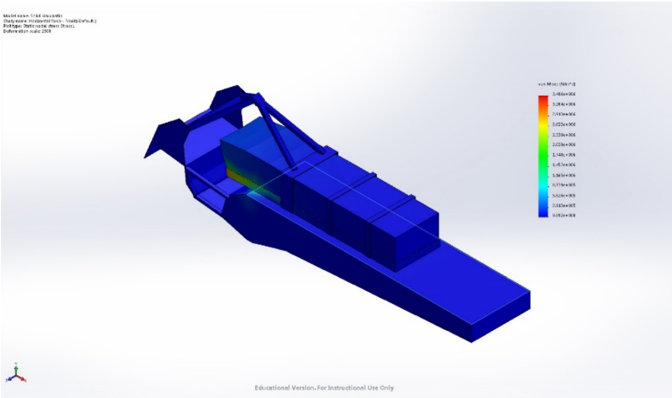

Figure 10. Von Mises stresses on sled chassis and battery container caused by 20G horizontal deceleration force in front.

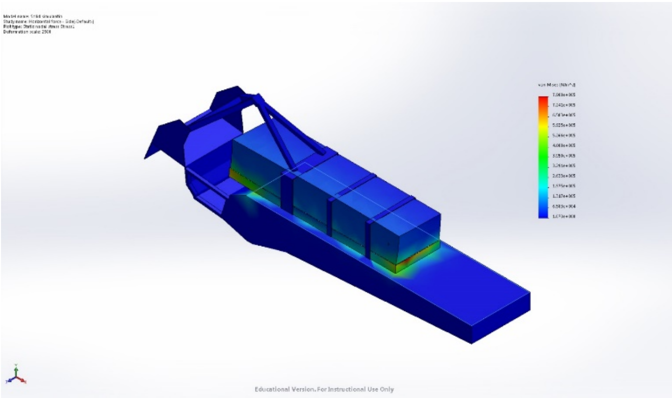

Figure 11. Von Mises stresses on sled chassis and battery container caused by 20G horizontal deceleration force on the left side.

The vertical simulation with 10G force gives similar results showing the chassis modifications and container comply with the requirements stated in these rules. The **Table 1** below shows the simulation results.

Table 1. Von Mises simulation results for different axes.

Axis	Load [G]	Force [N]	Max. stress [N/m^2]
Horizontal (front)	20	17070	3.496e+06
Horizontal (side)	20	17070	789952
Vertical	10	8535	211785
Battery container weight [kg]		87	
Yield strength [N/m^2]		275e+06	

The battery module support frame simulation results can be seen in **Figure 12**. The figure shows the support frame is robust enough to comply with the competition rules.

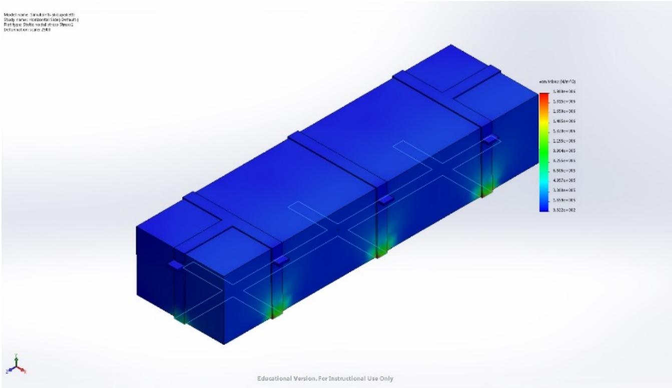

Figure 12. Von Mises stresses on battery pack and its support frame caused by 20G horizontal deceleration force on the right side.

The results for the support frame simulation are shown in **Table 2**. Same settings were used for the battery pack support frame simulation as with the previous simulation.

Table 2. Von Mises simulation results for battery pack support frame.

Axis	Load [G]	Force [N]	Max. stress [N/m^2]
Horizontal (front)	20	16200	3.42e+06
Horizontal (side)	20	16200	1.98e+06
Vertical	10	8100	297373
Battery container weight [kg]		80.5	
Yield strength [N/m^2]		275e+06	

Battery heating system

The snowmobile has a built-in battery heating system (**Figure 13**) to maintain safe charging and discharging temperature ranges. By heating the batteries we can extend the operating temperature beyond -15°C (5°F) and charging beyond -0°C (32°F). These limits are set by our battery supplier and are as low as they allow. Preheating the battery modules also reduces the power losses. The battery heating system is always active when the AC is connected to the sled. The heating elements have thermostats to keep the temperature at 20˚C (±5˚C).

The combined heating power is 160W @ 230VAC and 36.6W @ 110VAC. As a fully resistive load the heating power is optimized for 230VAC system. Without a regulator a 110VAC optimized heater would be dangerously hot when used in a 230VAC system.

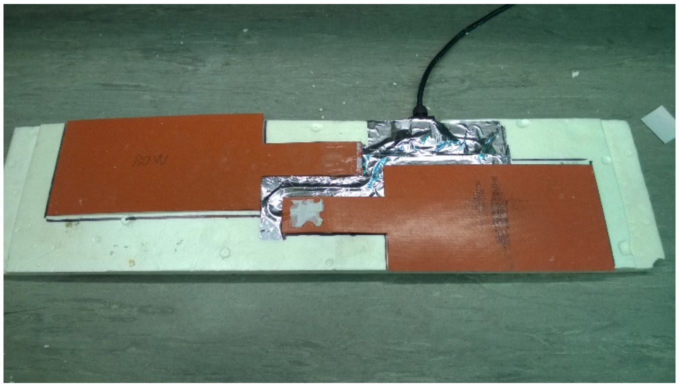

Figure 13. Two battery heater elements installed on heat insulating material.

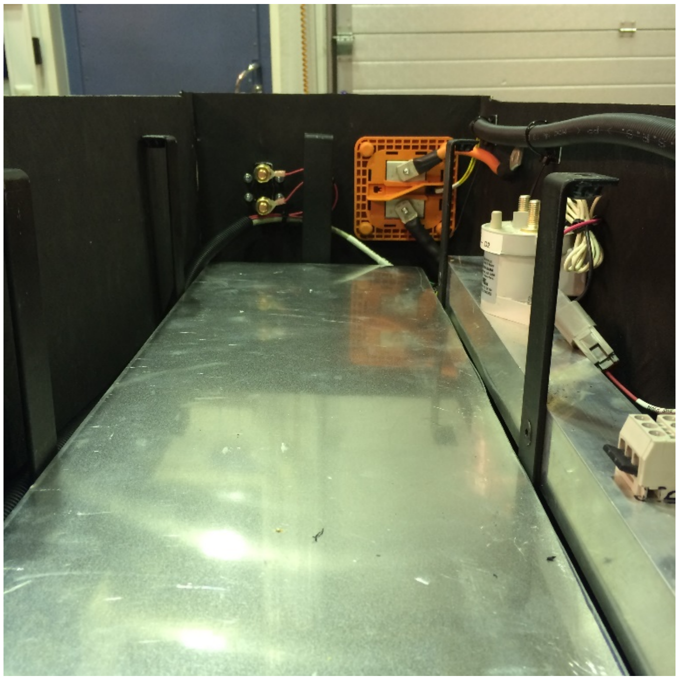

Figure 14. Battery heaters are located beneath the metal plate.

The battery heaters are installed under the batteries. There is a metal plate (**Figure 14**) between the heat elements and batteries to distribute heat evenly to the batteries.

Battery charging

Our team required the battery charger to be onboard, rugged, waterproof, lightweight, equipped with CAN-bus and commercially available. Eltek EV Power Charger was selected as it fulfills our requirements and in addition complies with the competition rules. The Eltek is capable of charging at 3kW power when used with 230VAC and about 1.5kW with 110VAC.

The AC inlet is located exactly at the same point as the fuel tank inlet in IC engine sled as can be seen from **Figure 3**. The AC inlet is J1772 compatible and it accepts J1772 compatible charging pistol. No external charging control or signal is required as the charging power is at J1772 Level 1 and the Eltek limits its intake power. Only requirement is J1772 pistol and cable equipped with compatible mains plug. Our team has J1772 charging cables equipped with NEMA 5-15 and Schuko mains plugs.

The battery charging process is controlled by the BMS. When the AC is connected, the GLV systems are powered on and the charging status can be seen on the dash display. Once the conditions are secure for charging to start, the dash signals the BMS via CAN bus to enter charging mode. The BMS controls contactors (BIRs) and sends periodic charge request message declaring charging voltage and current that should be used. The BMS must be continuously polled by the dash via CAN, otherwise it will shut down as a safety procedure and open the BIRs.

Electrical safety

HVIL

The sled is equipped with four high voltage interlock connectors. If any of those connectors is loose or not properly attached, the sled will not activate the traction system. One of these HVILs is located in the HVD and the other three are in the connectors of the charge cable, battery heater AC cable, and the traction system main power line.

Insulation Monitoring Device - IMD

While powered, the sled is continuously monitored by an IMD. The IMD our team has chosen is Bender ISOMETER® ISO-F1 IR155-3204. The sled waits for the IMD for the OK signal before activating the traction or charging system.

If the IMD gives an error signal the HV system is shut down. The error state will latch until manually reset by mechanic. Our team chose to place the reset button at the rear end of the sled and in the same container with the TSMP. By this, we made it easier for the operator to measure the insulation resistance manually before reactivating the system.

Firewall

We have constructed a firewall to prevent possible thermal effects from propagating to or from the battery container. Each battery module is sealed in flame retardant material in case of cell malfunction causing fire.

Remote telemetry system

The snowmobile is equipped with a remote telemetry system that is python programmable. The system is used for data logging purposes. We are using the same system in our other prototypes as well. All of the data acquired from the CAN bus is automatically sent to our server for later research and live tracking.

The type of the system installed is ConnectPort X5 R. We have chosen the model with X-Bee, WiFi and GPRS wireless interfaces. The model is easily replaceable with an Iridium compatible model.

MSRP

Our MSRP document includes every major part installed to the snowmobile. Some of the parts could be easily replaced or removed in a mass production. However the current MSRP reflects the prototype as it is. There are even some parts that have no role in the CSC competition and wouldn't be included by default in a mass production model but are only used for our own data acquisition and analysis. The $ 20 571 retail price reflects the 5000 sold units.

CONCLUSIONS

We have been concentrating on producing a visually pure and functional snowmobile with the modifications only necessary to fulfill the SAE CSC ZE requirements. In addition, we strongly wanted to follow our own design objectives; modularity, maintenance and commercialization.

We achieved in our objective of modularity by creating a system where all of the subassemblies are distinguished according to their function. For example the battery pack is replaceable with an alternative one with the similar interfaces.

Even the smallest mass production accelerates the development toward a better product. This makes it possible to direct more resources on continuous product development and further on a bigger commercialization.

We are content about succeeding in most of our maintenance objectives. Though there are some issues which need some more consideration; removing the battery container requires too many people and the wire routing does not perform the best solution possible.

We considered the safety issues in specially detailed level due to the commercialization requirements, which are user-safety, reliability, usability and affordability. Since the user-safety is the prior concern, we are proud to present the product fulfilling this demand. Considering the other commercialization concerns, we are not yet at the point to get the facts of our snowmobile. Those are naturally the issues that will be faced on future development processes of the sled and will be taken seriously.

ACKNOWLEDGMENTS

Our main organizations are Lapland University of Applied Sciences and Lapland University. In addition we have received a financial support from the Lapland regional council. Without these participants we would have not been able to make it. We want to address special thanks to following persons who work at the research and development unit Arctic Power of Lapland UAS; Ari Karjalainen, our supervisor, project engineers Juha Autioniemi and Toni Hämäläinen and other staff members who contributed in the project.

In America the organizers of the competition own our humblest thanks; SAE and MTU KRC, especially Jay Meldrum, who invited us to the competition, Danny Bocci, who was our ESF judge and of course Jerry the machinist. We also want to thank all other participating MTU KRC staff members.

DEFINITIONS/ABBREVIATIONS

BIR	Battery isolation relay
BMS	Battery management system
CSC	Clean snowmobile challenge
ESF	Electrical Safety Form
FPGA	Field Programmable Gate Array
HVIL	High voltage interlock
IMD	Insulation monitoring device
NSF	National Science Foundation
KRC	Keweenaw Research Center
Lapland UAS	Lapland University of Applied Sciences
MSRP	Manufacturer's suggested retail price
MTU	Michigan Technological University
TSMP	Traction system measurement points
ZE	Zero Emission
Iridium	Satellite network for voice and data communication