Efficient and reliable eSled Expedition 2.0

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Abstract

The Lapland University of Applied Sciences (Lapland UAS) is participating the CSC ZE for the second time in 2016 competition. Last year our team was victorious and we will be defending the title with our latest design. The snowmobile used in this year's challenge is built on a 2016 Lynx Adventure LX 600 ACE chassis. Compared to last year, the sled has been designed to have better performance. It's been upgraded with dual DC motor and additional battery. The added weight has been noted in our design as we have removed some unnecessary components compared to 2015 version to make up the weight of additional weight of dual motor setup and extra battery module. After our CSC ZE 2015 victory, we agreed with United States National Science Foundation (NSF) to deliver a slightly modified version of our CSC ZE 2015 sled to Summit Station, Greenland. Our team gained a lot of experience and insights on how to develop a reliable and functional sled for extreme conditions and what's the normal daily sled usage like at the Summit Station. We have implemented some new features to our sled based on our experiences and feedback from Summit Station.

Introduction

The CSC ZE 2016 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 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.

Design objectives

Performance

Our main design objective for this year was to improve our sled's performance. The experience and feedback gained from the Summit Station visit has been utilized in our design. The drivetrain of the new sled has been completely redesigned to enhance the sled's performance in draw events. Furthermore, one battery module has been added to the battery pack to achieve better range. The new design also includes removal of some unnecessary or obsolete components which will be discussed later.

Maintenance and modularity

One of our main objectives was to make a prototype that is easy to maintain and repair. This was one of our objectives in last year's event as well, but it was not completely reached in that design. The 2016 version includes several enhancements compared to 2015. For example, the Grounded Low Voltage (GLV) system has been completely redesigned to minimize the amount of extra wiring by utilizing the original snowmobile wiring harness and by designing a GLV PCB for interconnection of the signals and circuits required by the eSled components. These modifications, discussed later in detail, make our design even more modular and easier to maintain and repair.

CSC 2016 ZE specific design goals

Safety

Last year, the rules set by the SAE CSC, forced us to rethink and renovate the safety systems already installed into our pre-CSC 2015 prototype. This year there's no major changes in how the safety systems work and they fully comply with the CSC 2016 ZE rules.

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

Our low voltage (12V) system is grounded to the snowmobile chassis and there is an insulation monitoring device (IMD) monitoring traction system insulation faults. Other traction system safety features include a master switch, insulation error latching and manual insulation measurement points. In addition, motor controller and the BMS have their own built in safety features to shut down the traction system on fault condition.

Overall performance

As mentioned earlier, the feedback received from Summit Station has been noted and we have concentrated on improving performance, especially draw and top speed as well as maneuverability. Our sled has already proven to be reliable in extreme conditions which made it possible to concentrate on performance by upgrading the motor from a single unit to two similar DC motors. The upgrade to dual DC motor is described in detail later in the Modifications chapter. Most of the components used in this year's sled are same as in CSC 2015 competition.

Range

With our pre-CSC 2015 sled we achieved an average of 238 Wh/km (2.6 miles/kWh) (*Figure 1*). After the weight reductive modifications for the CSC 2015 the consumption decreased and we achieved range of 30-32km with that model. In the CSC 2015 our consumption in the range test was 170 Wh/km, which was better than expected. The conditions were in our favor and the sled was pretty lightweight (<300 kg).

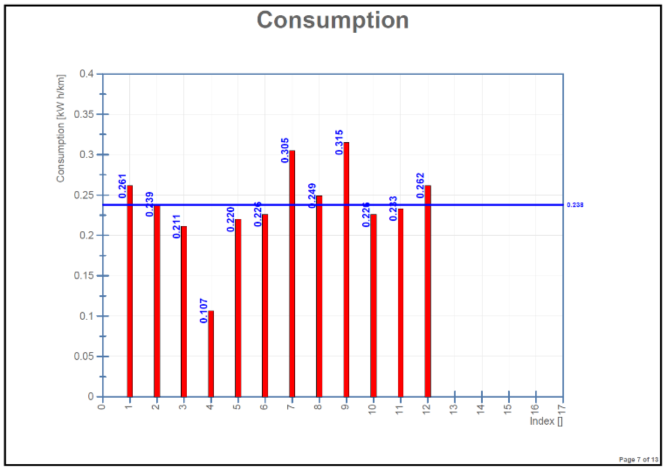

Figure 1. Consumption chart of pre-CSC2015 sled

At Summit Station the average consumption according to our recordings was 283 Wh/km mainly because of heavier weight of the sled. The sled was also nearly always towing test equipment and tools. Total range recorded during the Summit Station visit was 572 km.

Last year the sled was configured 3s1p with 4.96 kWh battery capacity. This year our 4s1p power pack contains 6.61 kWh of energy and we are aiming to improve the range to 40 km. The sled weighs 300kg which we achieved by carefully designing and selecting the HV system components and selecting light weight GLV components.

Draw Bar pull

We have limited amount of draw bar pull data. In last year's competition the draw bar pull test was performed on icy road and therefore the results were not satisfying. In 2015 competition's load event we successfully pulled the load the required distance. This year we expect to have improved pull performance as we have upgraded our motor.

We have tested the pull performance of our sled in practice last summer in Summit Station. The sled was heavily used in Summit Station crew's daily activities which included pulling test equipment and supplies. The feedback we received in their test report was very positive and they felt that our sled made their daily work easier.

Pull testing has been carried out for our 2016 design and preliminary results indicate that we have quite moderate pull performance. We tested the pulling capacity by towing a 315kg snowmobile in different scenarios and we are confident to perform well in the draw bar pull and load events. Only concern will be the conditions as we don't have studs installed.

Modularity

Interfaces

By opening the glove box, the user can easily connect to the sled's configuration interfaces for diagnostics and maintenance. Connections available are USB, Ethernet, CAN bus and RS-232. The USB interface is for the dash and the RS-232 is for the motor controller. Ethernet interface is for the remote telemetry configuration. All other devices are configured via CAN bus.

The interfaces are located in the glove box for the operator's convenience. There's no HV connections near these interfaces and the dash and indicator leds are clearly visible during configuration and diagnostics.

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 python programmable remote telemetry system enabling our team to monitor the sled performance and data in real-time. Along with the telemetry system we have installed a microcontroller to handle simple tasks like Ready-To-Drive Sound and error beeps. The dash, motor controller and BMS can be configured with programs provided by the manufacturers.

The eSled Expedition 2.0

Chassis

The chassis selected for the sled is a 2016 Lynx Adventure LX 600 ACE touring snowmobile. The selection was based on availability and familiarity of this chassis from last year's competition and Summit Station experiences. 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 our sled in action.

Figure 2. Our eSled built on Lynx Adventure 2016 LX 600 ACE chassis having final preparations before CSC 2016.

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 redesigned to make it possible to install the battery container on the tunnel. The new rear A-arm fits to original mounting points and is made of similar metal. Only difference is that it is slightly bent and is a bit longer.

Drivetrain

The drivetrain (*Figure 3*) has been completely re-designed to fit the double DC-motor assembly to the bottom of the engine compartment. The main original parts we have remaining in the current design from the base sled are drive shaft, drive sprockets and drive chain. The new drivetrain enables higher top speed and better torque compared to CSC 2015 or Summit Station versions. Estimated top speed of the sled will be approximately 65 km/h depending on the selected motor controller settings.

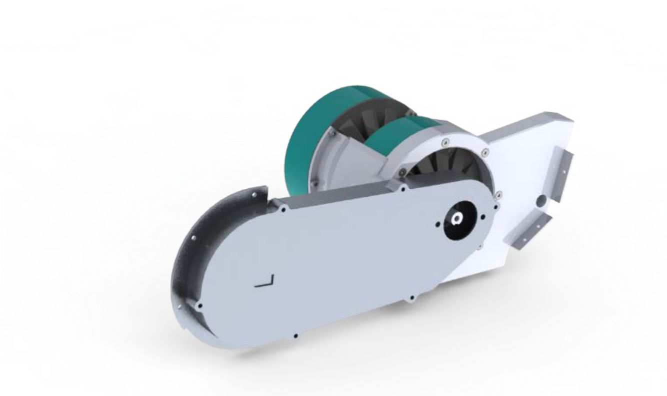

Figure 3. The re-designed drivetrain with dual DC motor attached.

Dual DC motor

Two LEM-200 D135 84 V brushed DC motors have been selected to be the motor of this year's sled. After CSC 2015, we upgraded from single to dual DC motor in order to achieve better pull performance in the upcoming Summit Station visit. The feedback and results indicated the upgrade was a success and therefore we chose to improve the dual DC motor design further.

Other main reasons behind the selection were its light weight (22kg), reasonable size and high efficiency (up to 93%). The motor has a peak power of 60kW while the rated power is 33.68kW. 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 moderate, the low RPM power is a disadvantage of brushed DC motors.

Figure 4. The upgraded CSC 2015 sled at Summit Station, Greenland.

In the Summit Station sled (*Figure 4*) the dual DC-motors were assembled on the original chain case with the CSC2015 motor adapters due to tight schedule. This decision made the sled a bit unsteady and changed its center of mass to the right. Additionally it was necessary to cut a hole to the right body panel to fit the motor. The re-designed drivetrain for the CSC 2016 sled solves these issues.

Dual DC motor assembly

It was required to design a new assembly for the dual DC motor. The motor should fit into the bottom of the engine compartment to be as low and as middle of the sled as possible to achieve optimal center of mass.

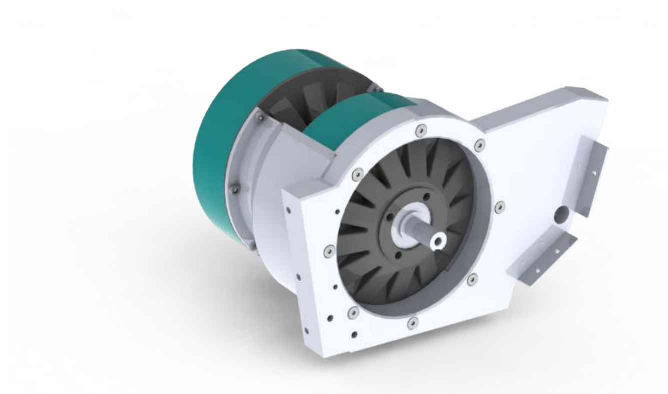

Figure 5. Dual DC motor mounted to the base frame.

The *Figure 5* shows the motor mounting assembly design drawing. The two motors are connected together with a shaft. The outer motor has two firm half circle cover plates attached which will mount it to the first motor and to the base frame. The base frame will be mounted to the chassis and it replaces the original right hand chassis member. The base frame is made of high quality aluminum alloy and it is designed to be stronger than the original part.

Chain case

As the motors are mounted to different location the original chain case can't be used because it is incompatible with the new motor assembly and position. Our team designed a new chain case which can be seen in *Figure 6* below.

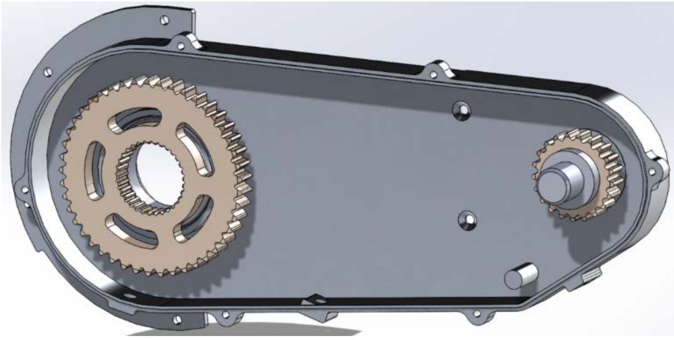

Figure 6. The re-designed chain case of the new drivetrain.

The new chain case is mounted firmly to the chassis and base frame and it is made of similar aluminum alloy as the new base frame. The new chain case has slot for the original RPM sensor and we also added a M6 threaded hole for oil temperature measurement.

It was also required to modify the upper drive sprocket to connect with the DC motor's axle. Our team designed modifications to the upper sprocket as can be seen in *Figure 7*. The center hole of the sprocket was widened to fit the DC motor axle adapter making the DC motor connection to the drivetrain possible.

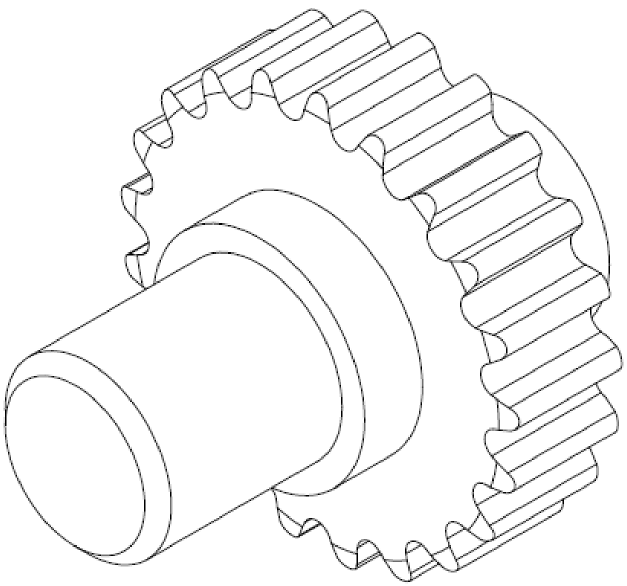

Figure 7. Modified upper drive sprocket with DC motor axle adapter.

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 CSC 2015 and Summit Station 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 8* shows engine dynamometer data on 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. For this year's competition we set the gear ratio to favor top speed because of performance of our dual motor setup.

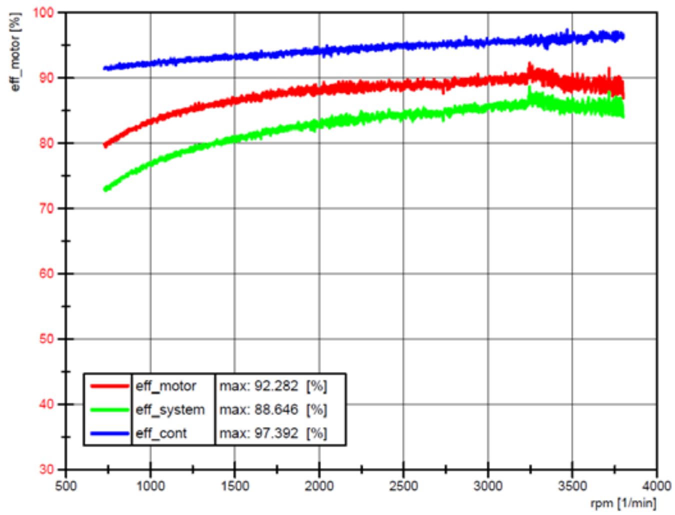

Figure 8. Typical efficiency data of single LEM-200 135 DC motor with Kelly HPM14701 motor controller. Tests have been done using engine dynamometer. The graph shows combined results of four separate tests.

Batteries

As last year, 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 9*) 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 9. 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

Compared to CSC 2015 we have added one module and redesigned the battery container to fit one extra battery module. Single U-Charge® U27-36XP battery module is configured as 12s33p. The battery pack of the sled is configured as 4s1p consisting of 4 U27-36XP modules in series. This accounts to total amount of 396 cells per module and 1584 cell per 4s1p battery pack. With this configuration we can reach 5.95 MJ of energy per module (C1 rate), totaling to 23.8 MJ for the whole battery pack which equals approximately 6.61 kWh. Nominal voltage of the battery pack is 153.6V and nominal capacity is 46Ah.

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 is built of 3mm thick aluminum and it is covered with UL94-V0 non-conductive plastic sheets to provide electrical insulation between the battery pack and firewall.

The batteries are fixed into the container using tight frames made of 3mm aluminum. Additionally, the battery modules are made of UL94-V0 non-conductive material providing extra layer of safety.

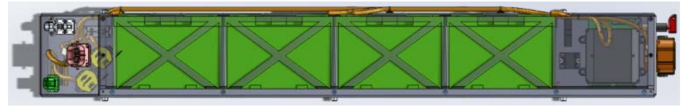

Figure 10. Top view of the battery container.

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.

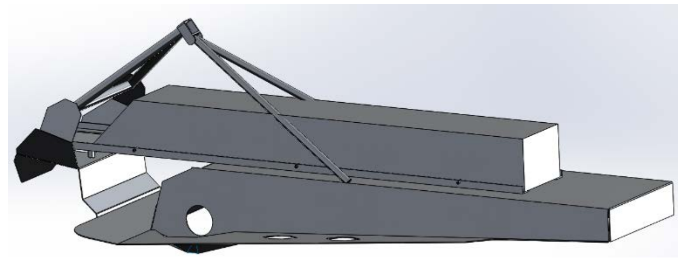

Figure 11. Battery pack mounted on the sled.

The battery container, container mounting, and chassis modifications have been simulated according to the SAE CSC rules using SolidWorks 2015 educational edition. The results show the container and runners are robust enough to withstand the 20G horizontal forces as can be seen in the *Figure 12* and *Figure 13*. The simulation figures show stress distribution in N/m^2 and the deformation scaling is set to 2500 to highlight the deforming areas.

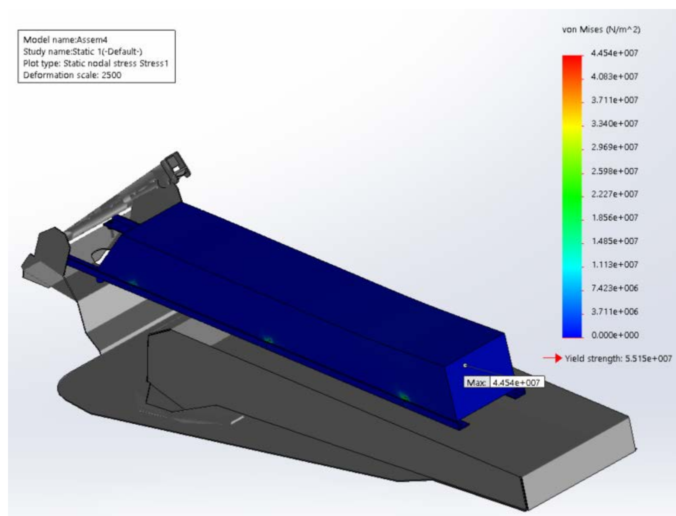

Figure 12. Von Mises stresses on sled chassis and battery container caused by 20G horizontal deceleration force in front.

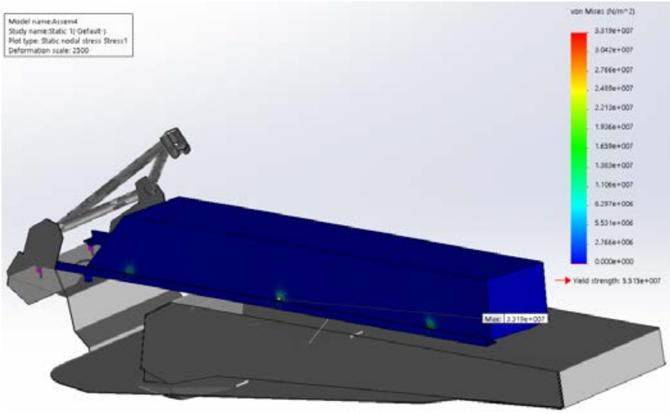

Figure 13. Von Mises stresses on sled chassis and battery container caused by 20G horizontal deceleration force on the left side.

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	20000	4.454e+07 N
Horizontal (side)	20	20000	3.319e+07
Vertical	10	10000	2.335e+07
Battery container weight [kg]		102	
Yield strength $[N/m^2]$		5.515e+07	

Battery charging

We chose to use same rugged onboard charger, Eltek EV Power Charger, as in CSC 2015. It is 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 ICE sled (*Figure 2*). 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, a signal is sent to the BMS via CAN bus to enter the 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 via CAN, otherwise it will shut down and open the BIRs as a safety procedure.

Electrical safety

HVIL

The sled is equipped with three 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 two are in the connectors of the charge cable and the traction system main power line.

Isolation 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. Additionally, 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 python programmable remote telemetry. The system is used for data logging purposes. 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 are specific for this prototype only and 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 $ 21 530 retail price reflects the 5000 sold units.

Conclusions

Having successfully participated CSC 2015 and Summit Station, our team has gained confidence and experience on designing electric snowmobiles which could on one day be commercially available. We are confident that we have succeeded developing a reliable, safe and modular electric snowmobile with moderate performance and range.

To achieve this our team had to redesign some major parts of the snowmobile such as the drivetrain. Though it is the first version of its kind, we are already confident it will perform well in the competition. Other major redesign was the GLV system. In the CSC 2015 the GLV wiring was pretty messy and we decided to redesign it for the CSC 2016. Implementing that we reduced the sled weight with almost 10kg by removing unnecessary parts and enclosures. We also simplified the HV system by removing some extra BIRs while still remaining rules compliant.

There is still room for improvement as our future plans include weight reduction of the current components and upgrade of the battery pack. There's also work to be done to simplify the GLV system further and utilize more original snowmobile parts such as the dash. We are looking forward to gain even more experience from the CSC ZE 2016 event to be utilized in our future eSled designs.

Acknowledgments

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In America the organizers of the competition own our humblest thanks; SAE and MTU KRC, especially Jay Meldrum and Danny Bocci, who was our ESF judge. 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
GLV	Grounded Low Voltage
HVD	High Voltage Disconnect
HVIL	High voltage interlock
IMD	Insulation monitoring device
Lapland UAS	Lapland University of Applied Sciences
MSRP	Manufacturer's suggested retail price
NSF	United States National Science Foundation
TSMP	Traction system measurement points
Iridium	Satellite network for voice and data communication