ME 491 Independent Study – Fall 2017

Mechanical Design to Test Novel Electric Vehicle Control

Ryan Connolly and Allison Heredia

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1 Project Background

Dr. Goetz’s lab seeks to apply their high-performance electronics, originally developed to control electrical pulses in noninvasive magnetic brain stimulation, to the battery systems of electric vehicles (EVs). The EVs currently on the market have a battery pack that always emits at its full 400 V voltage, a level that can be potentially lethal to humans. The battery pack rapidly switches on and off in order to supply the desired voltage and also involves a myriad of electronics to convert the battery’s DC power to three-phase AC for the motor or to 12 V DC for the entertainment and air conditioning systems.

The lab is pursuing an alternative system set-up, one that arranges the batteries in 12 individual modules with 40 volts each that can be activated in either series or parallel to output a sinuous wave. If executed correctly, this new design can result in benefits including outputs at a higher quality, efficiency, and lower cost as well as reduced wear on the motor and improved safety.

![Battery Modules in Dr. Goetz’s Lab](image)

Our team of four ME Undergraduate students, Steven Burcat, Ryan Connolly, Allison Heredia, and Connor Shannahan, was assembled in order to implement and test the novel EV battery and control system developed by Dr. Goetz’s lab into a small-scale working prototype. This mechanical design team had to address questions in regards to both the structural and thermal design of the EV.
2 Structural Design

Rather than building an entire vehicle from scratch, the team would utilize the existing frame of a buggy used by the Duke Electric Vehicles (DEV) club in the past (Figure 2). Using this frame gave the team a head start but also imposed several design constraints as the team had to figure out how to integrate the battery technology into a pre-existing space. On the back side of the buggy there were two metal shelves. The lower shelf had the old motor and controller and the top shelf was unoccupied. This top shelf was determined to be the space for the battery packs. The top shelf is 2 ft wide and 9 inches long with an additional 3 inches of length at a shorter width where the plate is bolted to the vehicle frame (Figure 3).

![Figure 2: Back Side of DEV’s Electric Buggy](image)

The battery system will be comprised of 12 modules, each containing three batteries and a circuit board. Aluminum L bars will be machined and arranged to surround and separate the batteries, providing a conductive path for heat to escape (Figure 4). The top aluminum L will extend beyond the battery itself to support the circuit board which is wider than the batteries. Our team designed and prototyped a 3D printed
frame to house the battery module and connect it to the vehicle. The design originally had four notches to slide the plastic frame onto T-slotted framing rails, but concerns about accuracy and vibration led to an alternate design utilizing t-slotted fasteners (Figure 5). The battery modules would be attached to two parallel 1” T-slotted rails with the fasteners, and the rails themselves would be attached to the metal plate with L brackets. Most of the required materials, including the x bars and some L brackets and fasteners, were available in the Duke Mechanical Engineering Department labs. Whatever materials that couldn’t be found in the labs were then ordered from McMaster Carr.

Figure 4: 3D Printed Models of Batteries and Separators

Figure 5: Sketch of Original Battery Module Design

A significant design constraint this problem faced was the size of the metal plate the battery modules were to be attached to. Several different arrangements and configurations were discussed throughout the design process including a rack to hold an elevated row, a row of batteries attached beneath the plate, and a single row extending well beyond the width of the plate with the help of the T-slotted framing. With every design option came a different concern including visibility for the driver, air flow to the batteries, and difficulties with wiring the electronics. A design was finally settled on with two rows of battery modules: a row of 4 in the narrower portion of the plate directly behind the seats and a row of 8 directly behind that
first row (Figure 6). This design proved to be beneficial on the electronic side of the design since the modules are wired together in groups of four. However, this design does come with concerns in regards to the thermal design, which will be discussed in further detail in the next section.

![Figure 6: Solidworks Model of Battery Arrangement (Top-Down View)](image)

### 3 Thermal Design

A primary concern and design focus for the implementation of the technology into the buggy is the thermal characteristics of the system. It is critical to ensure that the batteries and electronics are all properly cooled while in operation. In order to increase the efficiency of the cooling process, a large heat sink will be placed on the lateral sides of each battery module. An additional heat sink will be placed on top of the circuit board itself. Seeking heat sinks that are within the project’s budget, are the maximum size for the given space, and are tall enough to improve heat transfer to the ambient air, we settled on two different sizes of black aluminum heat sinks (Figure 7). A 120 x 69 x 27 mm heat sink was chosen for the lateral sides and a 40 x 40 x 11 mm heat sink was chosen for the top of the circuit board.

![Figure 7: Selected Heat Sinks](image)

Heat sinks alone, however, will not cool the system enough when it is in operation. Because of the scale of this project, the team decided that a liquid cooling system would be excessive, and decided to focus our efforts on utilizing the air flow through the buggy to create forced convection to improve the performance of the heat sinks. As previously mentioned, there was concern around the design choice to place a row of batteries directly behind the seats. To get an idea of how significantly the seats will affect the air flow...
reaching the rows of batteries, the team developed both a physical experiment and a software simulation.

3.1 Air Flow Experiment

Using the limited resources available to us, we created our own simulation of airflow through the buggy by zip tying several box fans in the front interior of the vehicle (Figure 8). The fronts of both seats were approximately 2 feet away from the wall of box fans. Due to the steering wheel, we were unable to include a second box fan on the driver’s side, leaving the right side with two fans and the left side with only one. Additionally in the set up, pieces of paper were used to block the two holes in each of the seats to mimic the "worst case scenario" of the buggy having two passengers. An anemometer was used to take measurements of the air flow rate at various locations both in front and behind the seats. The results of the experiment can be found in Table 1.

![Figure 8: Experimental Set Up of Air Flow Test](image)

<table>
<thead>
<tr>
<th>Position</th>
<th>Left Seat</th>
<th>Right Seat</th>
<th>Between Seats</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left Hole</td>
<td>Right Hole</td>
<td>Left Hole</td>
</tr>
<tr>
<td>In Front</td>
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<td>0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>Behind</td>
<td>0.55</td>
<td>0.6</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Table 1: Results of Air Flow Test

The results of the experiment did indicate an agreement with our hypothesis that the seats would disrupt the air flow to the back metal plate, but many sources of error led us to be skeptical that the numbers we
recorded accurately mimicked what air flow would be occurring while the buggy was driving. Such sources of error include: the box fans do not provide uniform flow, the air speeds were too low for the anemometer to accurately record them, there was significant ambient air flow, the fans were placed inside the buggy instead of in front of it, the fans may not have been placed at accurate angles.

3.2 Software CFD Simulation

The results of our air flow experiment reinforced the need to create a CFD simulation in order to get an accurate understanding of the disruption of the air flow. A simulation is also helpful for determining the geometry of the battery enclosure we will add as well as where fan placement will be the most effective. After remarks Dr. Simmons, our senior design professor, made in class about the inaccuracies of SolidWorks simulations, several members of our team began working with ANSYS due to its stronger CFD capabilities. This program, however, has a steep learning curve so in the meantime we decided to create preliminary SolidWorks simulations to provide an understanding of how certain design aspects affect air flow in the system.

The CFD simulation was initialized with a uniform entering air velocity of 20 mph to simulate an idealized scenario of the vehicle driving at this speed with no crosswinds. While analyzing the results, specific attention was given to velocity contours parallel to the channels of the heat sinks since cooling rates are dependent on air flow in this direction. Velocity contours for the battery system without any enclosure are displayed below in Figure 9, with the left image at the height of the circuit board on top of the batteries and the right image at the mid-plane of the lateral heat sinks. A key observation from these contours is that airflow drops to nearly zero around the batteries that are located behind the two chairs. This confirms the expected airflow trends of the system and provides numerical evidence for the requiring additional air flow by means of an enclosure and fans.

![Figure 9: (Left) Open Airflow Velocity on Top Heat Sink; (Right) Airflow Velocity on Lateral Heat Sinks](image)

A prototype model of the battery system enclosure was designed in SolidWorks with the intent on improving airflow over the heat sinks. The performance of various enclosure designs was analyzed by visual
comparison of the velocity contours to the contours without the enclosure. The top-down view of the velocity contours for one enclosure design is displayed below in Figure 10. Notable design components of this enclosure include: 3 equally spaced 80 mm radial fans on the back wall pulling air through the enclosure, an inclined top surface to force airflow downward, outward drafting side walls for additional airflow control. The fans were modeled using pre-defined radial fan curves within the SolidWorks Engineering Toolbox. The velocity contour visualizations show an increase in velocity over the back row of heat sinks as well as circulating air flowing over the shorter row of batteries going toward the back of the vehicle seats.

Figure 10: (Left) 3 Fan Enclosure Airflow Velocity on Top Heat Sink; (Right) Airflow Velocity on Lateral Heat Sinks

To better understand the circulating flow, a velocity cut plot in the vertical direction was created between the batteries located behind one of the seats (Figure 11). From this image, one can see that air enters the enclosure over top of the vehicle seats and flows toward the fans. While some air is pulled through the fans, the remaining air reverses direction and circulates through the lateral heat sinks toward the seats. This circulation occurs due to flow rate limitations of the fans, since not all the air in the enclosure is able to escape through the fans. Although this design results in increased airflow over both the top and lateral heat sinks, it also presents additional performance concerns. First, airflow hitting the back wall of the enclosure without a means of escape will result in a drag force on the vehicle. Additionally, if prolonged circulation occurs within the enclosure the air temperature will increase over time due to interaction with the battery components and have less of a cooling effect.
As an attempt to correct for these added concerns, a new design was created using two fans with double the previous flow rate capacity as well as two added 80 mm diameter ventilation holes. As shown in Figure 12, this design improved airflow along the side walls and allowed more air to exit through the back of the enclosure. The added ventilation also decreased the amount of circulation within the enclosure (Figure 13).
4 Next Steps

As the project currently stands, there are several tasks that need to be completed and will be addressed in the Spring 2018 semester. A prototype battery module was created earlier in the semester and now all materials are on hand and ready for the manufacturing process to begin once the lab makes the batteries available. On the design side of things, the larger task that still needs to be completed is finalizing a design for the fans, ducts, and enclosure based on the results of the simulations. Current thoughts are to have deflectors in the space between the seats to shape the flow through the channels between the battery modules and to have the top of the enclosure either lowered or at a steeper angle as to capture as much air flow as possible and force it down towards the modules closer to the vehicle seats. Additionally, further redesign and analysis of the back of the enclosure is necessary to ensure that the correct type and number of fans are used, as well as the best means of incorporating ventilation. During the design process, the team will also need consider power supply available to the fans from the battery system, additional aesthetic and functional criteria such as weatherproofing, and lastly budgeting.
References
