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Improved Operation and Protection Method for Marching Band Keyboard Platform

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Abstract

A team of four undergraduate senior engineering design students complete a project to create a mobile platform for the university marching band. Students perform the research, design, construction, and testing to specifications that they negotiate with the project sponsor. In doing so, they bring a project from a Technology Readiness Level (TRL) 2 to a TRL 8. They research what has been done in similar situations in general, finding that an effective mobile platform for piano and similar instruments in a marching band is rare. They assemble documents and equipment from an earlier design attempt, determining that the concept was valid but the technology as attempted was badly inadequate. In coordination with the band director, they negotiate specifications for the unit. They build a frame and platform in coordination with a mechanical engineering design team. They design a communications system to link the platform's music production to the stadium's audio system and to provide command and control of movement of the unit. They create a propulsion system of motors, electronic drives, real time control, and wireless communication to move the platform precisely as specified by a remote operator. Their energy management system provides sufficient and monitored power at point of use through control of energy distribution, application, and storage. The resulting unit performs as specified in four home football games, proving their completion to TRL 8. Methods whereby students learned to create a successful project are illustrated. The project was completed on budget and on time. Recommendations for further improvement are presented. Assessment of successful aspects of the project are given from a technical perspective and from a client perspective.

Background and history

The College of Engineering and University of Idaho Marching Band have collaborated on many senior projects in the past to help make shows, half time and otherwise, even more entertaining with some pretty impressive special effects. This partnership began by creating and coordinating the band's music to a colorful light show using the windows of a high-rise dormitory building several years ago. A motion-assisted drum harness was the next project, soon upgraded to a drummer-powered mobile drum platform with fixed LED configurations that were programmable in simple ways.[1] All band members soon sported LED-encrusted glasses frames. Engineering students designed both drum platform and eyeglass frames to flash in time to the music and to respond to programming. Musicians and engineers gave their equipment creative names, such as Bandbeesten, Bandbeesten Legacy, and more. [1]

When bands use pianos or keyboards, they are either on the sidelines or mixed into the venue's audio system. A laptop computer, on the sidelines, is now as common as any musical instrument in a band, marching or otherwise, but it is an input to a mixer in the audio system that supports a band's performance. There is ample evidence of this in performance literature, in news magazines, and even in the popular press.[2,3] Bands do not routinely have pianos or keyboards marching around the field in coreography. The literature does not list keyboards or pianos in typical synopses of marching band performance art.[4] Therefore, research into marching band performances shows that pianos and keyboards exist, but on the sidelines.[2]

Previous iterations of unusual instrument configurations for marching bands at this university were typically "one-off" designs. For example, the Bandbeesten project was a moving drum set, powered by the drummer, that could be manually controlled. [1,5] It could not support more of a percussion set than the drum player would normally carry or push. The additional capacity that its frame supported was a portable light show and associated batteries and microprocessors. Its LED display was impressive in action, but its platform was ill suited for any other instruments that the band might want to use. Therefore, the project at hand was created. In 2019, the first team to address this concept was not successful.[1] The current 2021 team set out to combine functionality for these previous projects into a programmable, reconfigurable, generic platform that could support a piano or keyboard within the on-field coreography. For the 2021 season, the generic platform appeared in its first manifestation: a marching, dancing piano.

Introduction and specifications

The band's technical staff handled everything related to music. This engineering project was the moving platform. Its goal was to design a platform that met the following specifications in negotiation with the band's leadership. These are similar to the specifications adopted by the earlier failed attempt: [6]

- Total Dimensions of 6’ x 6’
- Operate with a total curb weight of 800 pounds
- Powered by lithium based cells
- Battery life of 15 minutes or more
- Wirelessly controlled
- Translate and rotate independently
- Operate from 2 different frames of reference
- Incorporate sufficient and appropriate safety features
- Have wirelessly controlled LED light strips adorning the platform

This project incorporated work from a previous team.[1] We collected the results of the previous failed effort of this specific project. We also reviewed other, more simple but successful projects that had produced specific, more simple products as described above. The most recent past senior design project team, though they failed to make most of their specifications, described a generic product, designed and built a basic aluminum frame, obtained some motors and batteries, and put on paper a design concept, including some beta code, for operating and controlling the platform. Figure 1 illustrates the initial state of the project at hand.[7] The only functioning parts of the initial state are the integrity of the aluminum frame, the innovative configuration of the wheels for movement, and the motors selected.

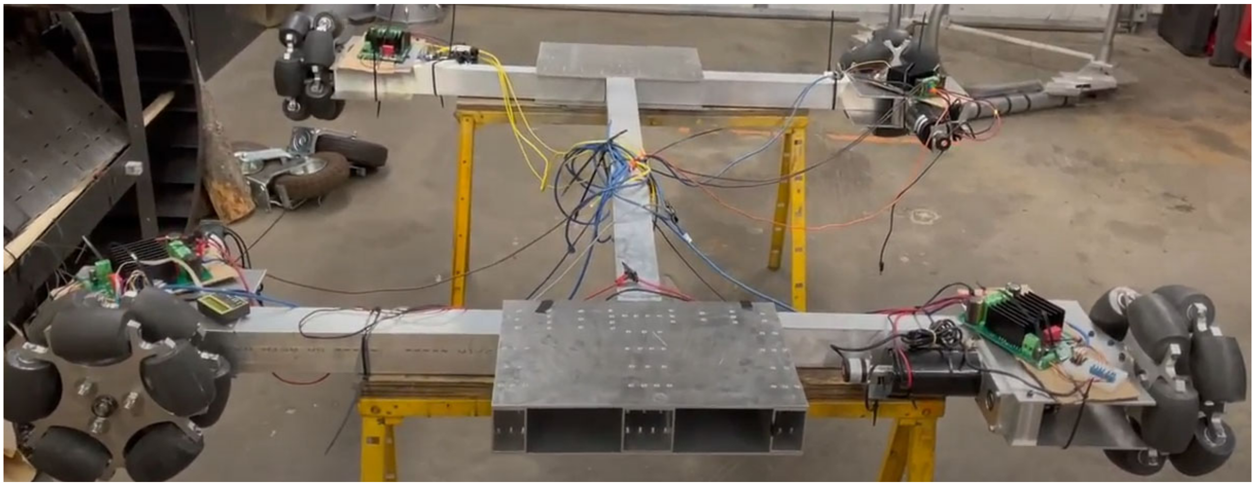
Figure 1. Incumbent platform and hardware.

System architecture

The overall concept design of the project was similar to the previous team's design but substantial advances were made to meet the new, enhanced set of specifications.[6] The platform was physically upgraded and all electrical equipment was designed from scratch and installed as shown in Figure 2. The following section describes components and interfaces.

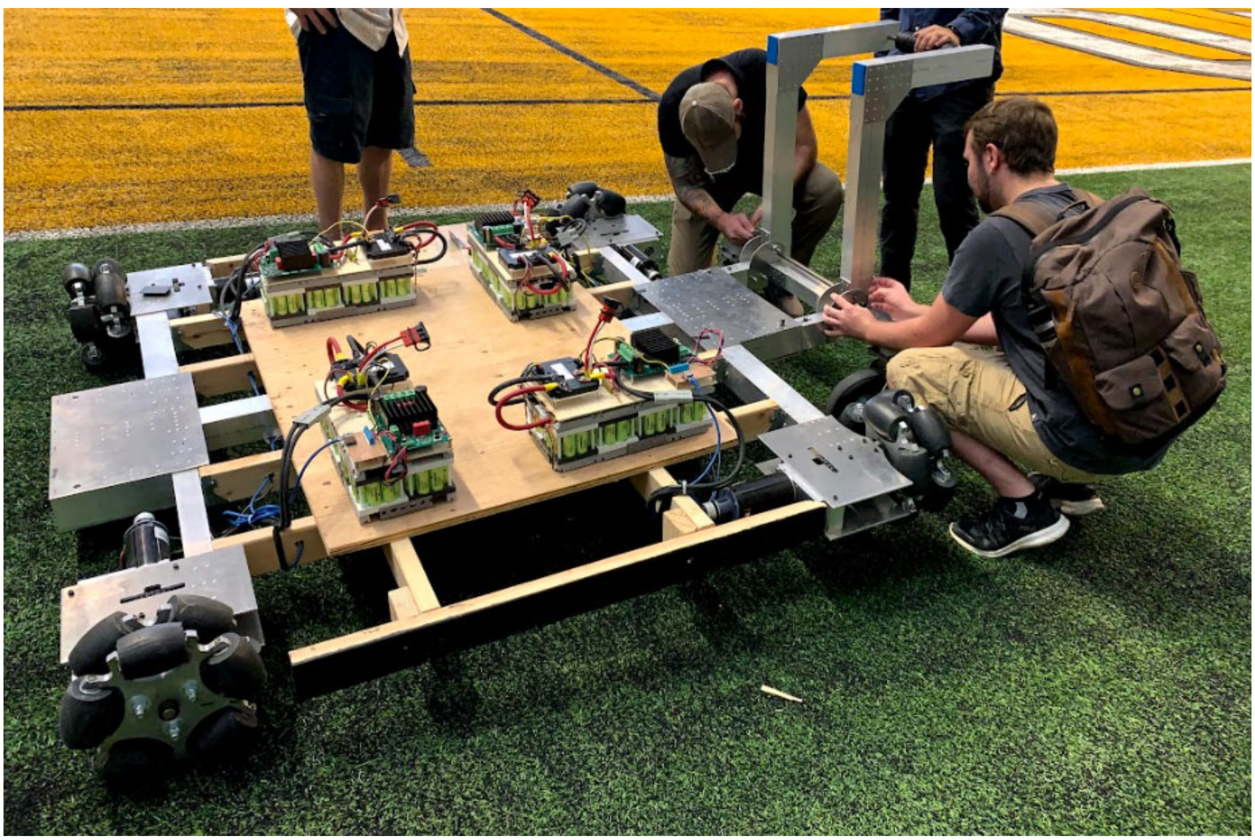
Figure 2. Platform configured for electrical build, program, and test

As an overview, the system's operation is as follows. There are four motors, powered by four separate battery packs with their own motor controllers and BMS units. These four boxes are then controlled by our two supervisory microcontroller units safely hidden beneath the platform. These microcontrollers read an input from our wireless FlySky remote using the FlySky receiver. This receiver has six pulse width modulated (PWM) channels from which it interprets the incoming data. The microcontrollers read the data and translate it into a PWM signal (speed signal) and direction signal that is sent to each motor over our RJ45 connections. These PWM signals and a set of three-axis direction signals are then received by each of the motor controllers. These motor controllers, one per motor, interpret these signals. They send the correct power of the correct polarity to each respective motor to get the motors to spin the wheels in the desired direction. As shown in Figure 2, the wheels move in an innovatively designed orthogonal fashion to enable translation or rotation or both simultaneously.

The main components for the project are the following, explained subsequently:

- Espressif Systems ESP32 Microcontroller
- Electromen EM282C Motor Controllers
- Roboteq 1040A Battery Management System
- BAE Systems ANR26650 Lithium Iron Phosphate Batteries
- AmpFlow F30-400 Brushed DC Motors
- MeanWell UHP-1000-36 Battery Charger

Two ESP32 microcontrollers were used in this project as the “brains” of the platform. These were picked due to their fast clock speed (240 MHz) which allowed for rapid control over motor PWM outputs. These microcontrollers also could create a wireless access point and host a small webpage. This option was used during testing to quickly and conveniently capture, update, and display global variables such as platform speed and rotational speed.

The EM282C Motor Controllers were adopted from the incumbent design. They suited project needs perfectly. Important characteristics such as ramp rates and overcurrent settings fairly easily with these devices.

The Roboteq 1040A BMS is a very robust battery management system. After installing the required software, it was easy to change the settings and to set safety limits as well as charging characteristics. Its software package has superb diagnostics, enabling the team to view the voltage levels and State of Charge (SOC) of our battery cells. This BMS is also capable of CAN and MODBUS RS485 communication, but time precluded adopting these.

The ANR26650 battery cells have excellent energy density and appropriate power output. The project currently has 256 of these cells powering the platform. By testing, the team confirmed that there is more capacity than necessary.

Motor testing revealed that the incumbent motors were inadequate. New AmpFlow motors were ordered. They have a lower rated speed but an improved torque capacity and torque response. This produced a better speed-torque match to the desired platform performance. Testing revealed that these new motors operated at a much better energy efficiency than the previous motors at the speed range designed for this project. This influenced our battery selection and battery cost.

UHP-1000-36 battery charger was chosen because it met all requirements. Previously specified BMS devices were over specified. This MeanWell charger is capable of 1008 Watts at 36 Volts and 28 Amps, matching our peak requirements, but having controls that are more effective at lower output power levels.

The remote controller is a Nordic Semiconductor NRF24L0 wireless transceiver system having an Arduino interface. It transmits 1Mbps reliably 40 yards without line of sight within the university's domed stadium under capacity crowd conditions. It transmits further distances throughout the entire stadium line of sight.

This new design is particularly notable for its interdependent protection and safety characteristics.

- The Enable signal is activated when remote controller is connected to the microcontroller, operating and confirmed. The Enable signal is necessary to connect the batteries to the unit. The platform cannot move without this activation.
- The motor controller has a time overcurrent limit of 80A for 150ms. The BMS has a time overcurrent limit of 100A for 200ms.
- The BMS has an instantaneous overcurrent limit of 150A. A large 150A fuse between the batteries and the BMS further protects these devices.
- There is a manual kill relay with redundant protection: Attached to the NC contacts is the BMS Enable signal which sets all BMS commands to ground when the kill signal activates. Attached to the NO contacts of the kill relay are the fault pins of all motor controllers, shorting all motor terminals to ground when activated. When this immediate and sudden connection to ground proved to be too severe a torque trajectory for the motors, the logic was changed to activate dynamic braking. The red lanyard that triggers this manual kill relay is shown in Figure 33, attached to the musician at the keyboard during a rehearsal.[5,7]

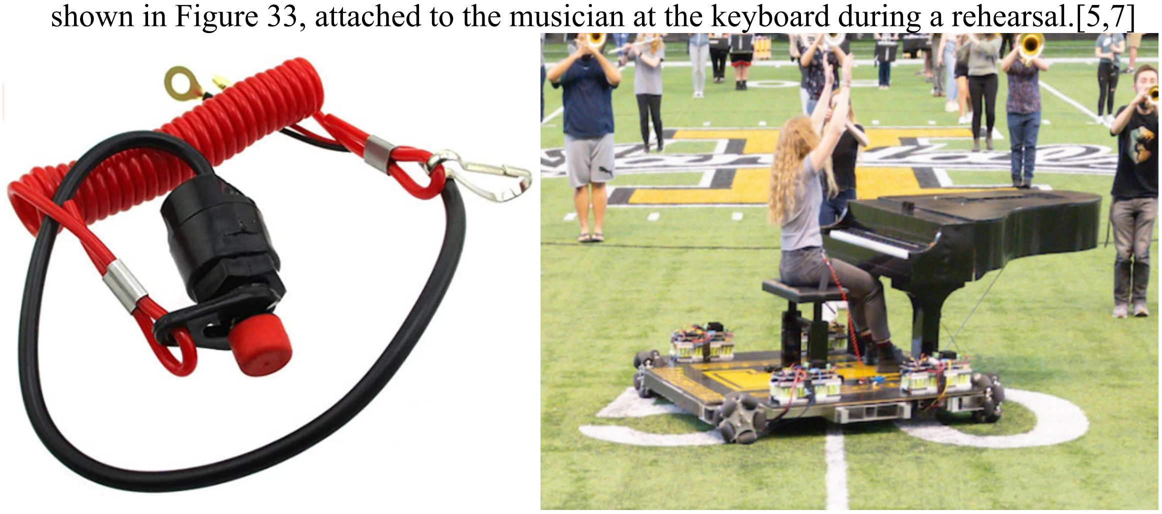

Figure 3. Lanyard kill switch. The red cord attached to the musician triggers the kill switch.

The musician plays the piano. She knows the marching and dance coreography, but she does not steer or control the platform. An operator with a remote control drives the platform. An audio based control unit, the same as those that operate the band's eyeglass frame dispays, operates the flashing LEDs around the platform.

Band performance defines battery requirements

The battery requirements were determined in close consultation with the band director. He defined a trajectory on the field: the unit would begin at the 50 yard line, rotate for 15 seconds about its center of mass, then drive laterally toward the end zone and off the field. This would be repeated five times. Rotation consumes somewhat less energy than linear motion because the former requires a light load on each of four wheel motors but the latter draws much larger power levels on only two motors at a time. The engineer team realized that success would breed greater requirements. They therefore used a test case of maximum forward acceleration for 20 yards, then immediate maximum reverse acceleration for 20 yards, returning to the start point. This was repeated for 15 minutes without pause. Though this is more than is possible while band is performing, it serves as a realizable worst case for this year's planned marching band coreography. The batteries were then selected and configured to meet this challenge.

The system passed this power and energy test on the field, though with some design iteration. The first set of tests resulted in a 73.8°C rise in motor temperature, activating motor thermal protection after 12 minutes of testing. Therefore, speed was limited to 5 MPH, about 60% of capacity. Because there was not sufficient time for significant mechanical improvements, the motors were replaced by more efficient and rugged versions in the same motor series. Testing under the planned trajectory was successful. The platform was then tested successfully with a full load of 450 pounds running at full speed the length of the field.. Test results are shown in Figure 4.[7]

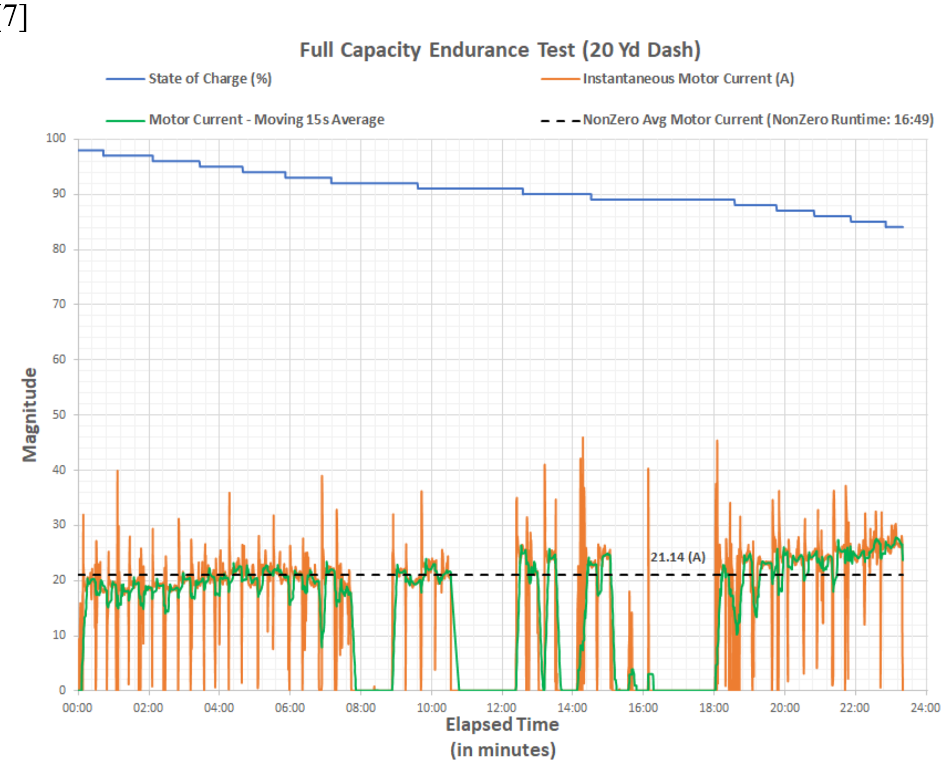

Figure 4. Test results of planned trajectory

True to the team's expectations, the band director and the stadium crowd were so impressed with the unit zooming off the field after rotating for 15 seconds that a new trajectory was requested. This time, the unit would enter the field, travel at full speed for 50 yards, do several short repositioning, spin, and dance movements, then zoom off the field at the end of the performance. The team's energy models predicted that the platform possessed the battery capacity to do this. Tests on the field verified that the platform did so and that the battery models were accurate in predicting battery performance.

The completed unit is shown in a laboratory in Figure 5.[7] When the paper is presented at the conference, video of the unit in operation at a football game will be shown.[9] In the video, the piano enters at 5:45 with the musician playing while moving and dancing. The piano performs several dance moves and spins. The students and professors who created the unit are credited on the audio before the piano makes a dramatic exit stage right at 13:20 in the video.

Figure 5. Completed unit in the laboratory

Design Failure Mode Effects Analysis (DFMEA) and Sustainability

The original design had at most one failure mitigation strategy -proposed for each subsystem. A DFMEA analysis verified this to be the case. Therefore, importance was given to a much more thorough design for failure mitigation, redundancy, and safe failure modes. As a result, Risk

Priority Numbers dropped tenfold. In any case, the musician rider is always tethered to the redundant kill relay as described earlier in this paper. The system became far more safe to operate, much safer than an initial inspection may lead one to estimate.

The system was built with sustainability and longevity in mind. The platform has a strong aluminum frame under a wooden support frame. Electrical components were selected conservatively, overdesigning appropriately in every instance. Multiple layers of current protection were used as described. The batteries have a 10,000 cycle lifetime. They should last many years under expected usage trajectories and loads. The team selected rechargeable, recyclable Lithium Iron Phosphate batteries, the safest lithium batteries available. The versatility of platform construction allows for a host of ways to use this platform. By using a single platform for many of the band's needs, instead of multiple smaller ones, the overall material cost of this project goes much further.

Budget

Project expenditures were a combination of a few big purchases that dominated the budget and miscellaneous electronic parts and construction materials. The largest single purchase was the four new motors for $1300. The second largest purchase was replacing one of the four battery management devices, damaged during one of the charge cycles, for $375. Our final large purchase was our battery charger at a cost of $270. These three purchases total up to $1,985 and make up 67% of our total expenditures. The remaining large expenditures came from the wooden platform and "fake" grand piano effigy. Other parts included the frame needed for mounting our batteries, as shown in Figure 6, a host of small parts, and an LED array. Total for the entire project was $2,980.

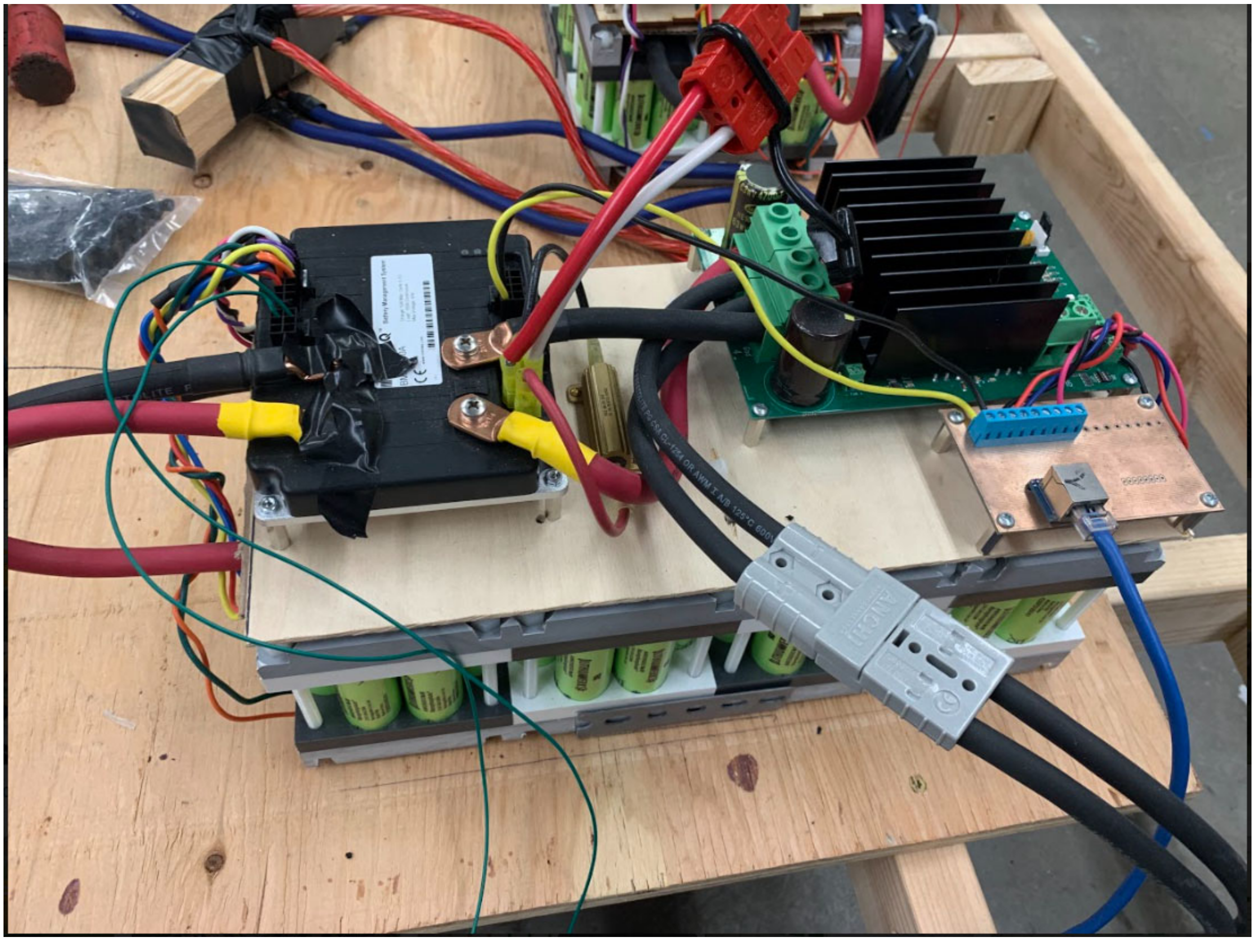
Figure 6. Battery enclosure and BMS.

Future upgrades

As with any successful project, there remain more upgrades to do.

- ESP32 microcontroller alternatives: The ESP32 does the job well but it is sensitive to platform noise. Other more capable alternatives merit consideration as technology advances.
- PCB design: Much of the electronics are on perf board. A professional PC Board should replace this to obtain better ruggedness and appearance.
- Build a more rugged, easier to load and maintain battery box.
- Install a better position referencing system. The current system relies on an operator observing the platform from a seat in the stadium, either on the sidelines or high in the stadium. A better, closed loop positioning system would fit into the planning of performances more neatly, automated with both automatic and manual safety override.
- Taking advantage of the BMS ability to communicate via an RS485 interface and CAN communications protocol. This would improve the speed and capacity to monitor more functions, such as motor temperatures, battery state of charge, speed and position of the platform and wheels. This information can be further used to enhance safety.

- Redesign the drive wheels. They are currently located at each corner of a square platform, oriented 90 degrees from their neighboring wheels. An orthogonal configuration is easier to control but it presents a heavier load on the wheel motors.
- Build a set of quickly interchangeable platform musical equipment setups.

Assessment

From a technical perspective, the system's performance meets specifications. It performs reliably as specified. It is a reconfigurable platform that moves to the expectations of the marching band. The band director was involved at the beginning of the project, negotiating the specifications. When the unit began testing, the band director again participated, providing interpretation of his expectations in the context of specifying an appropriate trajectory for the unit. This led to improvements in motors and batteries that solidly met the band director's expectations for trajectory and performance.

The band director accepted delivery. He used the unit in the first home game it was available. The band director appointed one of the team to operate the equipment during public performances. He specified a trajectory which the team accurately implemented manually. He used the unit again, with modifications in trajectory, for each of the remaining three home games.[9] The unit appeared in the band's part of the School of Music's annual Christmas concert in December. In other words, the sponsor voted with his feet, maximizing use of the equipment at every opportunity. The technical design was successful   And the client relationship was likewise successful. We will soon be forming a new team of undergraduate engineering students to continue this successful arrangement.

This project fit within the framework of senior design projects that has been in place at this university for more than twenty years. Salient aspects include multidisciplinary teams, either integrated or as cooperating entities, as this project had in its mechanical and electrical design teams. The framework for this senior design project was as specified in [8]. The result was a strong design experience and a satisfied client who anticipates a continuing relationship.

Conclusions

A senior undergraduate design team defined, created, developed, built, tested, and fielded a mobile platform to enhance marching band performance.This platform enables the university's marching band to include a piano or keyboard in the coreography of a marching band's field performance.   Beginning with a concept barely existing at TRL 2, the team negotiated a set of technical specifications with the sponsor. These specifications defined well the expected product's performance. From design fundamentals taught in a senior design course and using their technical education, the students created a working design of the product. They brought to bear on the problem various aspects of their education gained in classrooms and labs, their literature search and appropriate reading and viewing, their knowledge of various important subsystems gained by experience on and off campus, and guidance from their mentors and contacts.   They outlined major subsections of the project, then developed and completed design details. They then built each subsection and combined and interfaced the project into a complete, functioning prototype. Of particular note is a novel and thorough protection and safety subsystem, notable for its interdependent characteristics, that dropped Risk numbers tenfold from the same system design without such a subsystem. They fielded the completed prototype. It performed flawlessly at TRL 8 levels in the university's most public forum. The band now uses this platform regularly, a strong sign of a successful project.

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