ATHLETE:
Low Gravity Testbed

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Final Project Report
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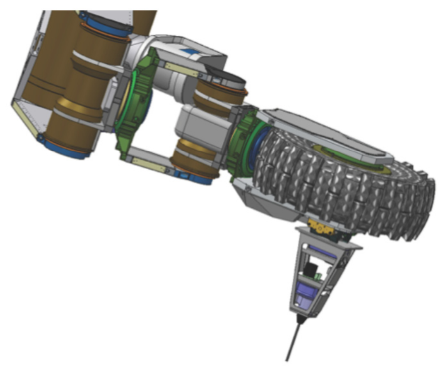
September 27, 2011

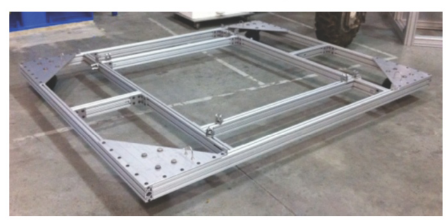
The All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) is a vehicle concept developed at Jet Propulsion Laboratory as a multipurpose robot for exploration. Currently, the ATHLETE team is working on creating a low gravity testbed to physically simulate ATHLETE landing on an asteroid. Several projects were worked on this summer to support the low gravity testbed.

Primary Project: Rotary Percussion Drill Tool



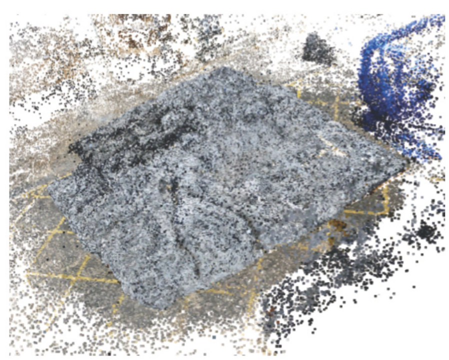
The primary project this summer was the design of a rotary percussion drill tool prototype for use with ATHLETE. Work involved mechanical design of the tool package structure and electrical design of the control system. The following final project paper covers this project in more detail.

Secondary Project: Habitat Dolly



A secondary project involved the design of ground support equipment for transporting the mock lunar habitat. A dolly was needed that could carry the habitat or the ATHLETE pallet while being mobile outdoors on lab, able interface with a forklift, and able to fit in a moving truck. This project involved creating a design concept using solid modeling CAD software, and finally assembling a working prototype.

Secondary Project: Asteroid Surface Mapping



Another secondary project was creating a procedure to produce a surface mesh of a mock asteroid surface for use with the ATHLETE low gravity testbed. The physics simulation powering the testbed requires a representation of the surface geometry of the asteroid surface. A procedure was developed using the software Microsoft Photosynth and Meshlab to create a point cloud and surface mesh from a series of photographs of the mock asteroid.

ATHLETE:
A Rotary Percussion Drill Tool Package for Rock or Ice Drilling

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Abstract

The All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) is a vehicle concept developed at the Jet Propulsion Laboratory based on the wheel-on-limb approach to mobility, allowing it to drive, walk, climb, and even manipulate its environment with its limbs. Through a standardized fixture and a clamp mechanism on each limb, ATHLETE is able to extract various tool attachments from a ”tool belt” as necessary during exploration missions. A rotary percussion drill tool package concept was designed to integrate with ATHLETE’s quick-disconnect tool clamp with the purpose of allowing ATHLETE to drill into solid rock or ice surfaces. This tool concept was developed to be simple, robust, and versatile, using a commercial rotary percussion drill mechanism powered by an easily changeable rechargeable battery and controlled wirelessly. The design also includes a mechanism for ATHLETE to change drill bits. With such a drill tool, ATHLETE would be able to drill into rock or ice during potential missions on the Moon, other planets, or asteroids, whether for anchoring, obtaining core samples, or other tasks.

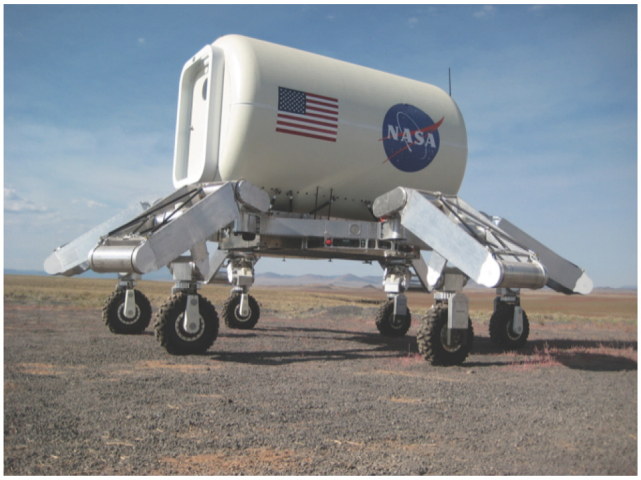
1 Introduction and Background

Robotic vehicles will play important roles for any potential future manned and unmanned exploration missions of extra-terrestrial surfaces such as asteroids. For potential manned missions, the vehicles would need to be capable of supporting the astronauts by carrying cargo and providing mobility [3]. The All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) is a vehicle concept developed at the Jet Propulsion Laboratory (JPL). The wheel-on-limb concept is the central idea behind the ATHLETE robot. This setup allows ATHLETE to efficiently traverse both gentle terrain and difficult terrain, using the wheels for driving over the former and locking the wheels and using the limbs as legs for the latter [10]. Because the wheels are only used for gentle terrain, ATHLETE is able to achieve mass savings through smaller wheels and limbs as opposed to traditional rovers which need large wheels for low ground pressure and high torque actuators [3]. ATHLETE was first designed as a utility vehicle for lifting heavy or bulky cargo in support of human lunar exploration [4].

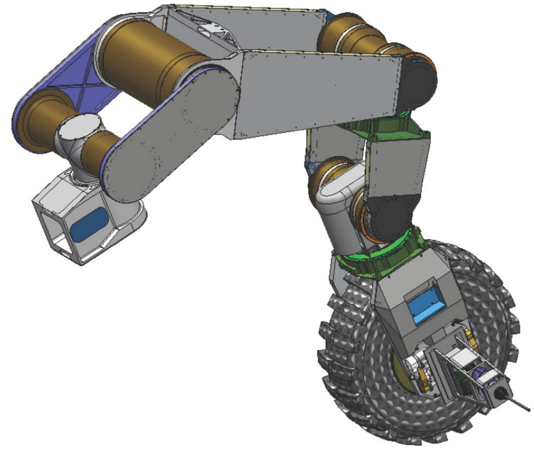
The first-generation ATHLETE has six limbs, each with six degrees of freedom (DOF): hip yaw, hip pitch, knee pitch, knee roll, ankle pitch, and ankle roll. These six limbs also each have a wheel attached. [10] The second-generation realization of ATHLETE was designed in 2008 in the form of two three-limbed vehicles called Tri-ATHLETEs. These vehicles can function independently without cargo, but are also able to combine on either side of a pallet for cooperative movement. Together with one vehicle as a master and another as a slave, the combined two-vehicle-and-pallet system is six-limbed like the first-generation ATHLETE [3]. Since the vehicle is stable on a minimum of only three of its limbs [3] and each limb acts as a general-purpose manipulator because of the walking ability, the robot is able to use limbs with tool attachments such as a gripper or an auger that can be extracted from a “tool belt” to manipulate the environment [10].

While asteroids have been studied from afar for many years, there is increasing interest in the study and exploration of asteroids. The Japanese spacecraft Hayabusa recently was able to successfully land on the asteroid Itokawa in 2005 and return to Earth in June 2010 [8]. NASA’s Dawn spacecraft is scheduled for orbit insertion at the asteroid Vesta in July and later to visit the dwarf planet Ceres, to study their structure, density, composition, and other characteristics that will help understand their formation and evolution [9]. Since many asteroids, like Vesta, have existed relatively unchanged over the history of the solar system, studying these asteroids can help shed light on the formation of the solar system [8]. Asteroids have also been discovered to have both water ice and organic compounds. These findings have supported the theory that Earth’s water and the chemical compounds that led to life may have come from asteroids [5]. President Obama has set a NASA goal of sending astronauts to an asteroid by 2025 [2].

While on a real mission, especially to a near earth object such as an asteroid, ATHLETE would likely encounter a situation where drilling into solid rock is required [6]. A drilling tool that integrates with ATHLETE’s quick-disconnect tool adapter would allow ATHLETE to drill into solid rock surfaces as necessary. Such functions may include drilling holes to lay anchors to address the microgravity environment on asteroids or to obtain a core sample for scientific analysis. With asteroid exploration as primary motivation, a prototype drilling tool for solid surfaces is needed for demonstrating ATHLETE’s capabilities in extraterrestrial exploration.



(a) ATHLETE rover prototype carrying a mock lunar habitat.



(b) Rendering of ATHLETE leg with a drill tool attached.

Figure 1: ATHLETE rover and rotary percussion drill tool.

2 Design Objectives

The following design requirements were identified in defining the objectives for the tool package

- **Integrate with ATHLETE's tool clamp**. The tool must be compatible with ATHLETE's existing quick-disconnect tool clamp.
- **Self-powered**. In order to be modular and easy to integrate and use, the tool should be self-sufficient without requiring an external power source or diverting power from ATHLETE.
- **Wirelessly controlled**. ATHLETE operators must be able to control the tool without a tethered wired connection, which would be complex and impractical.
- **Robust and reliable**. The tool must withstand the rigor of repeated physical tests and field trials.
- **Simple and inexpensive**. Given limited budget resources, the tool should be cost-effective and easy to manufacture.

3 Design Philosophy and Approach

Since this drill tool is being developed as a prototype for use on Earth, design choices were made with Earth-environment usage in mind. An equivalent tool designed for use on actual asteroid missions would have different requirements, such as large temperature variations and dust contamination. Materials and features appropriate to Earth would not be used on asteroids.

3.1 Drill Mechanism Selection

Rotary percussive hammer drills combine the chipping percussive action and the cutting rotary action to allow drilling into hard rock surfaces. The effectiveness of these types of drills make them a powerful tool for ATHLETE to bring on extraterrestrial missions, not just to asteroids, but extending to lunar, planetary, or comet expeditions where drilling into solid rock or even ice surfaces may be necessary [6].

For this design, the drill mechanism from an off-the-shelf Bosch 36 V Lithium-Ion Compact Rotary Hammer Drill was selected. An well-known off-the-shelf product such as this Bosch drill can be depended on to be reliable and high quality. While this approach has the tradeoff of forcing design choices to conform with the existing drill mechanism, the assurance that the drill mechanism would work properly was deemed more important.

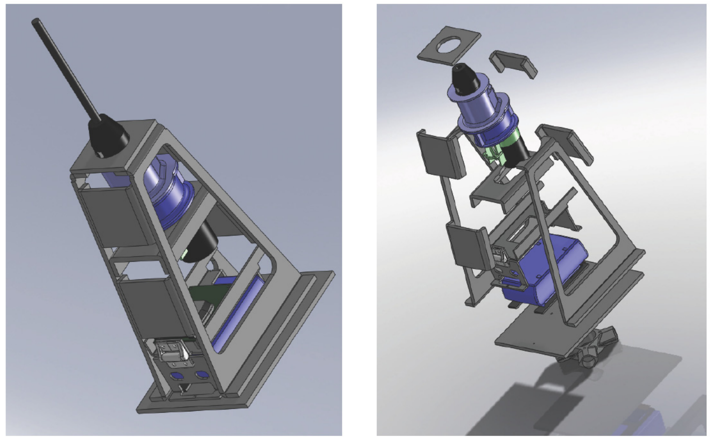
This particular model of drill was chosen also due to the extensive experience the laboratory has had with it in the past. JPL engineer Paulo Younse previously designed a rover arm-mounted rotary percussion drill using the same Bosch drill to demonstrate core sample obtainment for a potential Mars sample return mission. Current projects, including a robotic gripper project under Dr. Aaron Parness and a comet sample return concept under Dr. Paul Backes are also planning to use this Bosch drill. Choosing the same drill allowed leveraging existing designs and experience to jumpstart the process for developing the tool.

The drill motor, motor controller, and the battery from the off-the-shelf Bosch drill were also used in the design. Using these components reduced the work necessary to select new equivalent components and integrate them with the mechanism, and they would also work well with the drill mechanism.

3.2 Mechanical Design

The drill mechanism and other important components were to be contained in an enclosed package. For the package structure, aluminum alloy 6061-T6 sheet was the material type chosen to be used. Sheet metal parts are strong and stiff and can be easily cut with water jet using easily accessible facilities at JPL, and 6061-T6 is a durable yet inexpensive material to use.

Analysis was performed following preliminary design models to verify that all structural parts met requirements when subjected to specific load cases. If a part was deemed to be inadequate, it would be modified and reanalyzed. This process was iterated until the design satisfactorily withstood the load cases.



(a) Normal view. (b) Exploded view

Figure 2: SolidWorks rendering of tool package design.

3.3 Electrical Design

The motor, motor controller, and battery from the off-the-shelf Bosch drill were retained for use in the drill tool. This strategy ensures that given the proper input to the motor controller, the drill would behave the proper, expected way. Characterizing the electrical components, particularly the interface between the trigger switch and the motor controller was performed to identify how to integrate those components with the ATHLETE operator setup. Bluetooth was chosen as the wireless communication technology because ATHLETE already has a built-in Bluetooth transmitter. A microcontroller would be able to translate commands received over Bluetooth to the proper input signals for the motor controller.

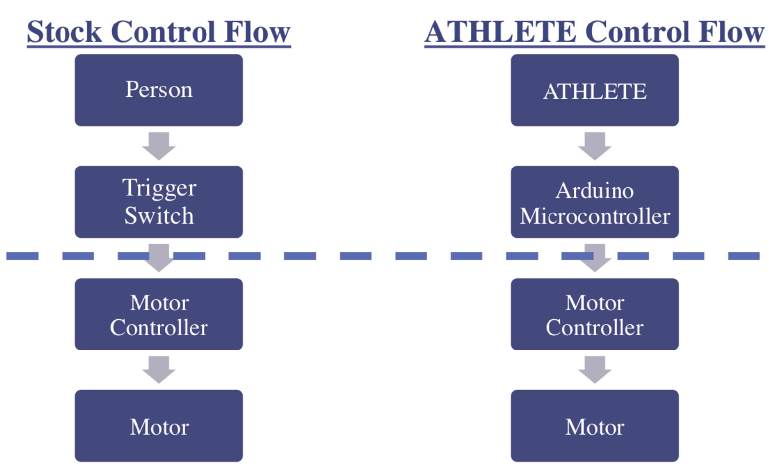


Figure 3: Flow chart illustrating approach to designing the ATHLETE tool control flow in comparison with the off-the-shelf drill. The motor controller and motor are kept, but the trigger switch is replaced.

A proof-of-concept circuit was constructed on a breadboard to demonstrate the design, and a printed circuit board prototype was then fabricated as a complete, compact system that could actually be used with the drill tool.

3.4 Bit Change Mechanism Design

Several bit change mechanism concepts were explored to be implemented on a separate bit holder "tool belt". By keeping the drill tool and the bit change mechanism separate, the tool being maneuvered could be kept light and simple. This modular design means the drill can be used whether or not a bit change scheme is implemented or not. Any bit change mechanism would require some kind of bit repository regardless, making this separated concept a logical choice.

4 Details of Current Design

4.1 Mechanical Design

Tool Package Structure

The tool package structure consists of many parts made out of aluminum alloy 6061-T6 sheet. All structural parts are ¼″ thick, with the exception of the battery cover which is ⅛″ thick. Two side plates serve as the primary structural components while also acting as the sides of the battery enclosure. These rest on the base plate, which is attached to the quick-disconnect tool clamp adapter. The drill mechanism housing attaches to the overall structure via top and lower cross plates. Finally, four brace plates on the open sides of the structure increase overall rigidity against lateral bending and torsion.

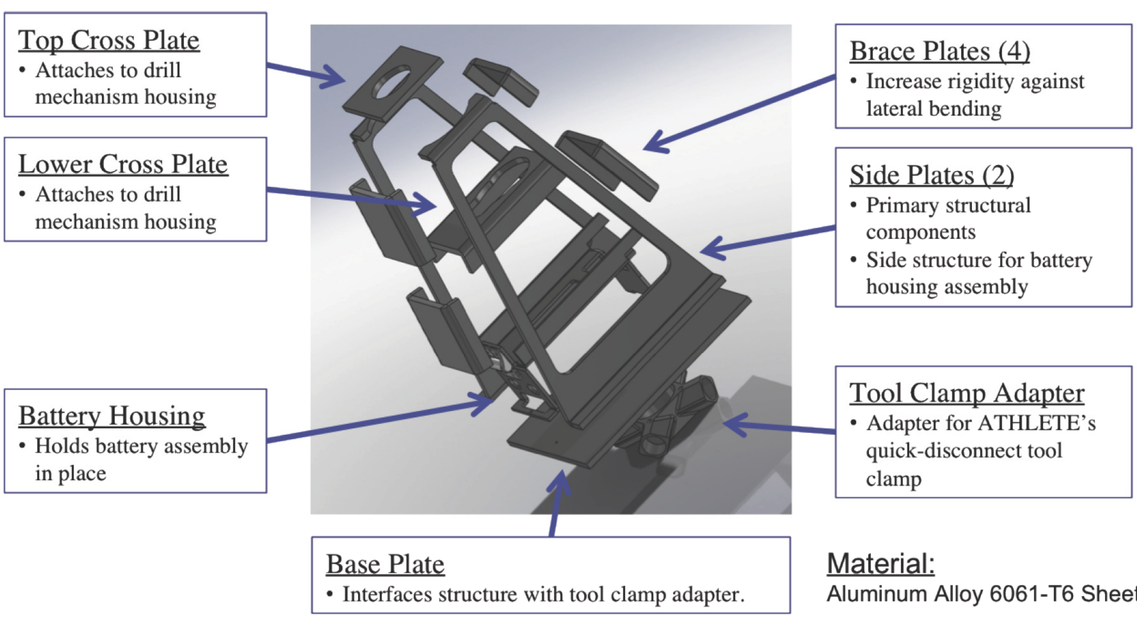


Figure 4: Labeled SolidWorks rendering of tool package structural components, exploded view.

Finite element analysis using SolidWorks Simulation was performed on the tool structure design. Five load cases were considered and all loads were applied on the surfaces of the top and lower cross plates that interface with the drill housing flanges.

1. **Straight drilling**. Drilling normal to the surface. An 800 lbf axial load was applied against the tool structure. This represents an error in operation causing ATHLETE to apply the maximum force possible through its limb.
2. **Angled drilling**. Drilling at a 45° angle relative to the surface. 800 lbf was applied both axial and laterally at 20″ away from the base plate. This load represents an error in operation; angled drilling should not be done with any preload, particularly with the ATHLETE limb maximum.
3. **Ventral tip load**. Drill bit hits obstacle while moving, in long plane of structure. A 500 lbf load was applied in the dorsoventral plane at 20″ away from the base plate.
4. **Lateral tip load**. Drill bit hits obstacle while moving, in short plane of structure. A 340 lbf load was applied in the lateral plane at 20″ away from the base plate.
5. **Stalled motor**. Motor stalls while drilling. An 800 lbf axial load and a 50 ft-lbf torque was applied, representing the maximum drilling force with a typical high-end drill motor stall torque.

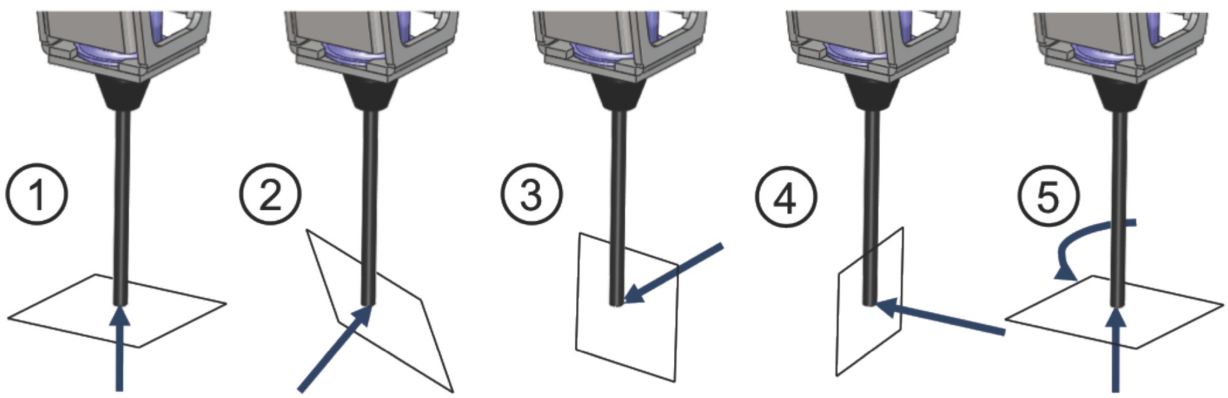


Figure 5: An illustration of the five load cases considered for finite elements analysis of the tool package structural design.

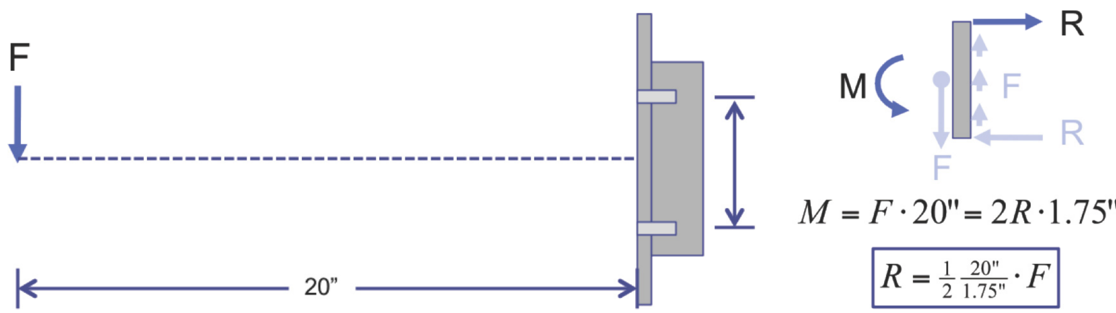
Bolted joints were assumed to absolute with no gapping and with shear loads carried by friction. The assembly was fixed at the surface on the base plate that interfaces with the quick-disconnect tool clamp. The typical ATHLETE margin philosophy calls for minima of a 1.5 factor of safety on material yield strength and a 2.0 factor on ultimate strength [1]. Factor of safety is defined as material strength divided by applied stress. For aluminum alloy 6061-T6 sheet, the yield strength is 35 ksi and the ultimate strength is 42 ksi [7]. By applying the margin philosophy, a 2.0 factor on ultimate strength gives a lower maximum stress, at 21 ksi. All following factor of safety calculations are therefore taken with respect to the ultimate strength.

Table 1: Finite Element Analysis Results

Load Case	**Load**	**Maximum Stress (ksi)**	**Safety Factor**
1: Straight drilling	800 lbf axial	5.3	7.9
2: Angled drilling	800 lbf axial, 800 lbf lateral	20.2	2.1
3: Ventral tip load	500 lbf ventral	20.5	2.1
4: Lateral tip load	500 lbf lateral	20.7	2.0
5: Motor stall	800 lbf axial, 50 ft-lbf torque	16.7	2.5

The results of the Finite Element Analysis is presented in Table 1. Additionally, a buckling study was performed with load case 1 to find a buckling factor of 97.6, a large margin over the critical buckling factor of 1. To see the von Mises stress plots, see Appendix A. From these results, it is concluded that the tool structure safely can handle loads far above typical use and many situation that may result from a robot malfunction or operator error.

Heel-toe loading on the tool clamp due to side loads, such as in load cases 3 and 4, were also analyzed. The existing tool clamp design uses four #10-24 bolts, making this tool clamp adapter-base plate joint beyond the control of this design. A side load was applied at 20″ away from the base plate, and gapping was defined to occur when the tension in a fastener exceeded the preload. The following equation was used to calculate the maximum force that could be applied before gapping occurred.



(a) Illustration of loading. (b) Free body diagram

Figure 6: Illustration of heel-toe loading on tool clamp adapter-base plate interface.

Table 2: Heel-toe maximum load calculations before fastener gapping

Hole Type	**Preload (lbf)**	**Max Load (lbf)**
Tapped Hole	1,231	215
Threaded Insert	1,578	276

From the results in Table 2, it is seen that the maximum side load the tool is able to take is limited by gapping of the tool clamp adapter fasteners to 276 lbf with threaded inserts, lower than the 340 lbf found from the finite elements analysis. This joint is still able to handle fairly large forces; however, options to increase this limitation would be to either shorten the design structure to reduce the moment arm or to create a new tool clamp adapter that attaches to the base plate with larger bolts.

Battery Enclosure

An enclosure composed of several different parts hold the battery in place. The battery used is the Bosch Litheon® 36 V lithium-ion battery that is used with the off-the-shelf drill. In this application, the battery is oriented upside-down relative to typical use with the original drill. The battery slides on a acrylonitrile butadiene styrene (ABS) rail. This rail is attached to the base plate of the structure and is plastic to reduce friction. The original battery terminal from the off-the-shelf drill fits into a cutout in the plastic rail so that the contacts slide into the battery. The terminal is attached to the base plate both with a screw and epoxy adhesive. A strip of teflon tape insulates the contacts on the rear of the terminal from the metal base plate. A sheet metal housing piece provides the top and the back of the battery enclosure. This piece attaches to the side plates on top and the base plate in the bottom-rear and also feature slots for the battery terminal wires and for facilitating removal of the battery. Finally, a hinged door holds the battery in from the front and also provides for easy access. A thumbscrew holds the door shut.

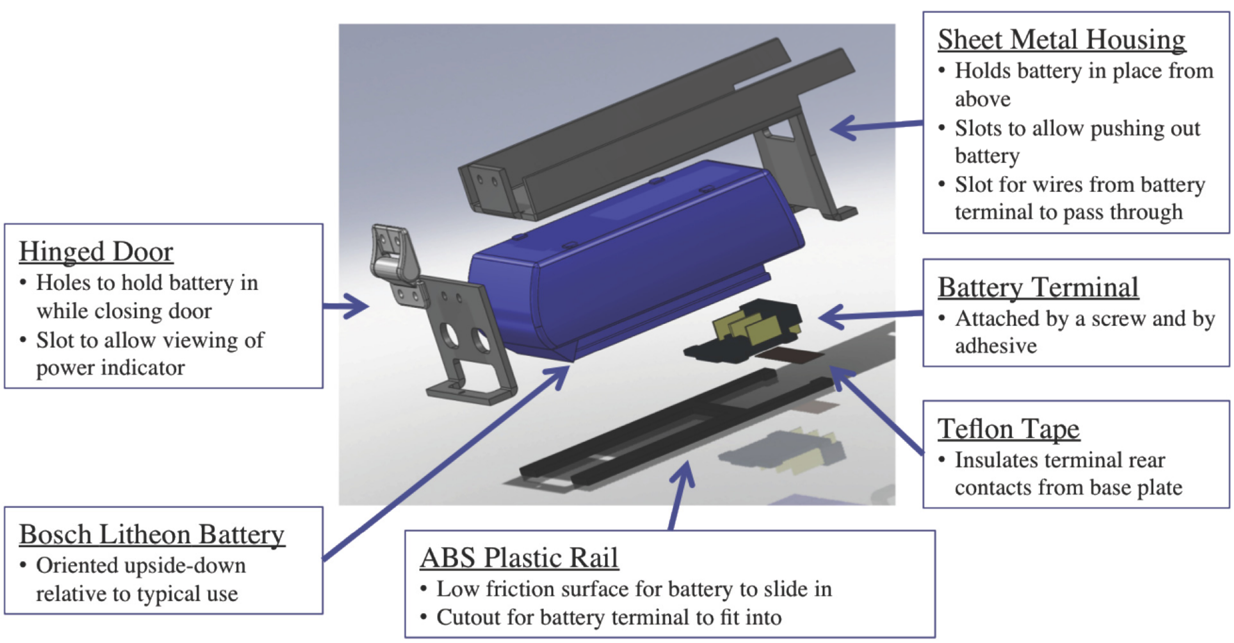
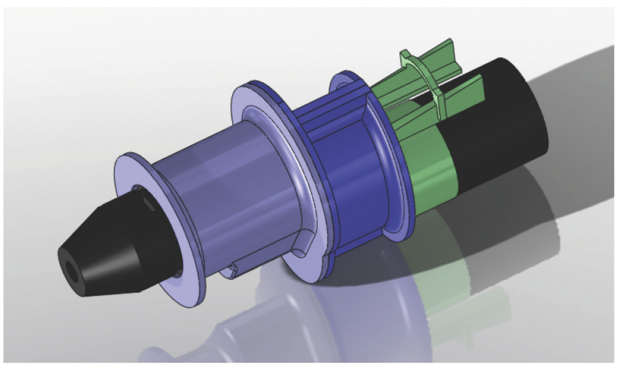


Figure 7: Labeled SolidWorks rendering of battery enclosure assembly design, exploded view.

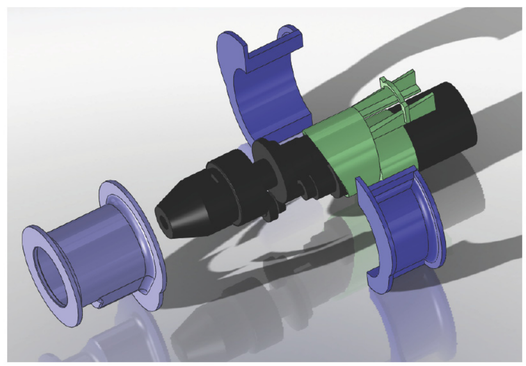
Drill Mechanism Housing

The drill mechanism assembly is contained in a housing to help hold it together during operation and to secure it to the tool package structure. The housing consists of three separate pieces: a front cylindrical part that slides on from the front of the mechanism assembly, and two rear half-cylinders that clamshell around the mechanism assembly. The front and rear flanges attach to the package structure, while bolted joints hold the three pieces together at the middle flanges.

The housing parts are to be fabricated using selective rapid sintering (SLS) with the material NyTek™ 1200 CF at ⅛″. This material is comparable or greater in strength to typical acrylonitrile butadiene styrene (ABS) plastics, and the thickness is comparable to the original housing from the off-the-shelf product. The SLS rapid prototyping method with plastic parts is much less expensive than producing similarly shaped parts out of a metal such as aluminum through milling.



(a) Regular view



(b) Exploded view

Figure 8: SolidWorks rendering of the drill housing design together with the Bosch drill mechanism.

4.2 Electrical Design

Electronics System

The existing electrical components were characterized by scoping the connections between them while running the motor. The trigger switch and the motor controller communicated over a six-pin ribbon, whose pins' functions were identified through testing. Pins 1, 3, 5, and 6 were found to be relevant for use in ATHLETE drill tool. Pin 1 provides 36 V power from the battery to run the motor controller. Pin 3 sends an analog DC voltage between 0 V and 5 V (produced by a potentiometer voltage divider in the trigger switch) to control the motor speed. Pin 5 and 6 indicate to the motor controller whether to go forward or reverse. Pull-up resistor circuits in the motor controller keep both pins at 5 V, and grounding pin 5 sets forward while grounding pin 6 sets reverse. The Bosch Litheon battery was also discovered to communicate an encoded digital signal through a third terminal to the motor controller, without which the motor controller would not run the motor.

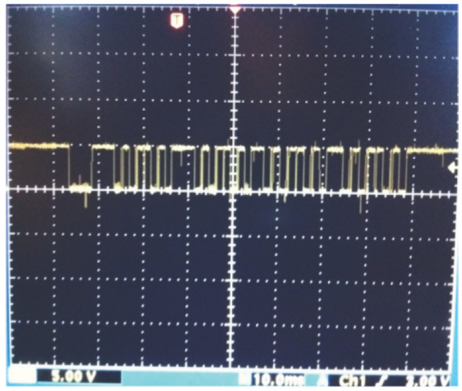
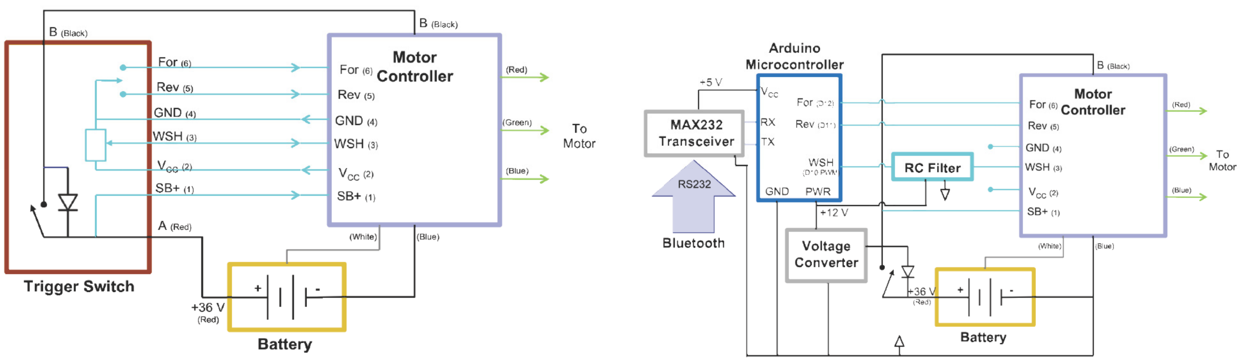


Figure 9: Scope of encoded digital signal from the Bosch Litheon battery to the motor controller.

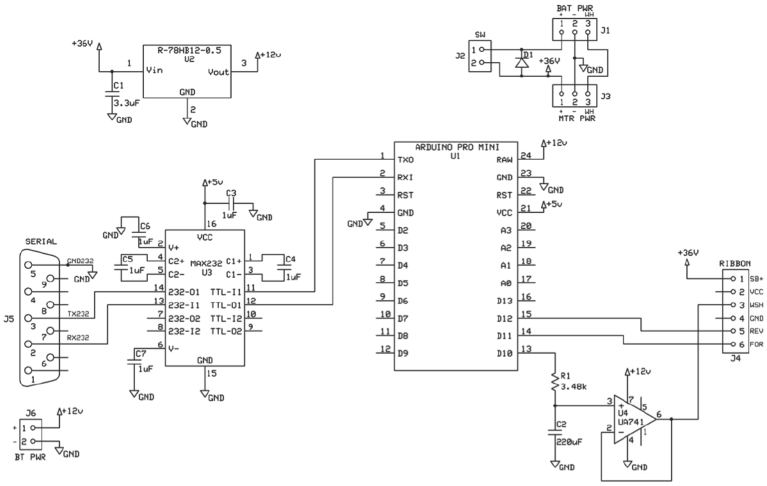


(a) Off-the-shelf circuit.

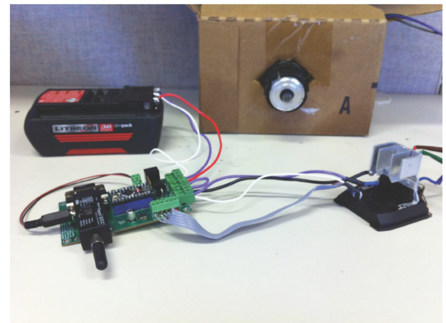
(b) ATHLETE circuit.

Figure 10: Schematic comparison of off-the-shelf electronic control system with the ATHLETE electronics design.

An electronic system featuring a Arduino™ microcontroller was then developed for use in the drill tool with ATHLETE. A Parani™ SD100 Bluetooth antenna, the same as the one in use inside ATHLETE, sends commands over RS232 serial to the microcontroller through a MAX232 transceiver. The Arduino Pro Mini microcontroller was used because of it provided all necessary functions while being easy to integrate and program. A simple low-pass resistor-capacitor (RC) filter circuit converts the pulse-width modulation signal from the microcontroller into an analog DC voltage to be read by the motor controller. A large ratio, 2400, in bandwidth frequency to pulse frequency was chosen to effectively attenuate rippling in the output analog signal. An op-amp serving as a unity gain voltage follower buffers the filter from the motor controller to reduce voltage drops across the filter. The microcontroller and op-amp were powered with 12 V from a DC/DC voltage converter.



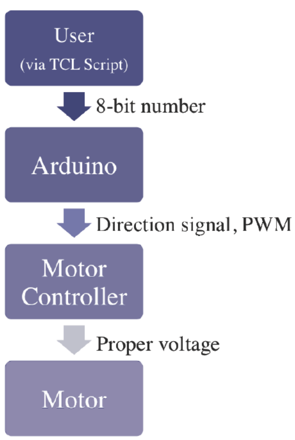
(a) Printed circuit board schematic diagram.



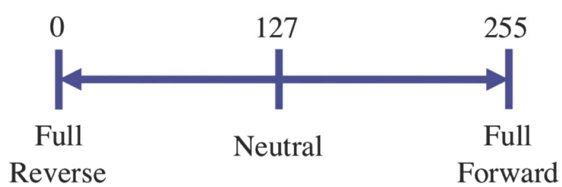
(b) Photograph of completed electronics system prototype.

Figure 11: A printed circuit board prototype was assembled.

The electronic circuit design was tested and proven on a breadboard to work as expected. A printed circuit board (PCB) was then designed and fabricated as a prototype for use in a full drill prototype. The completed PCB was then tested and verified to work correctly.



(a) Flow chart of software communication scheme.



(b) Scale showing how an 8-bit user input translates to motor movement.

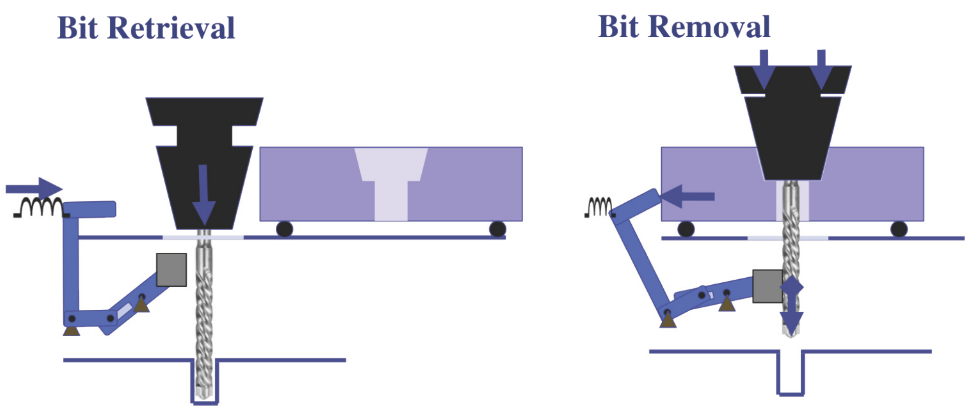
Figure 12: Electronics control system software design.

Software Design

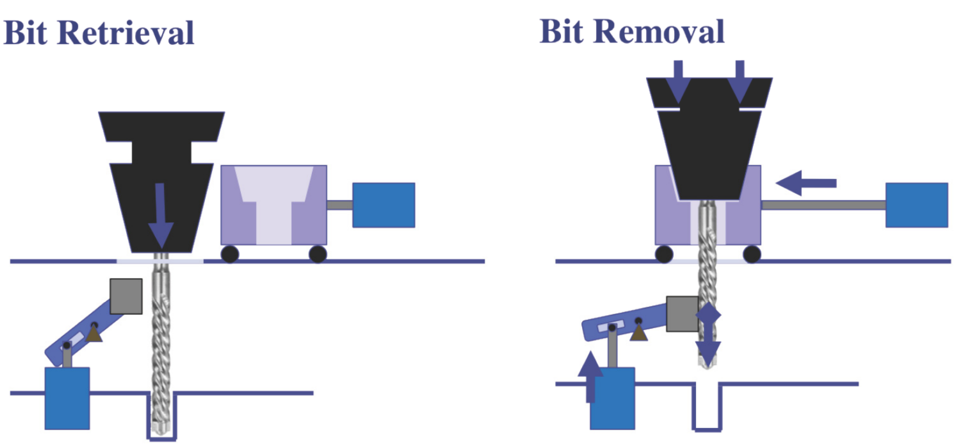
The software for controlling the drill was designed to be simple yet effective. The rover operation would send an 8-bit number via a TCL script over Bluetooth. This number indicates both speed and direction, with 0 representing full reverse, 127 representing neutral, 255 representing full forward, and intermediate values scaling to intermediate speeds in the respective directions. The Arduino microcontroller would then interpret this command to send a direction signal and a PWM speed signal to the motor controller. Control software for the microcontroller was written in the Arduino software language.

4.3 Bit Change Mechanism

The off-the-shelf Bosch drill features a SDS-plus drill chuck. Inserting a bit simply requires pushing the bit into the chuck until it clicks into place. To remove the bit, the collar must be pushed back and then pulling out the bit.



(a) Passive concept.



(b) Actuated concept.

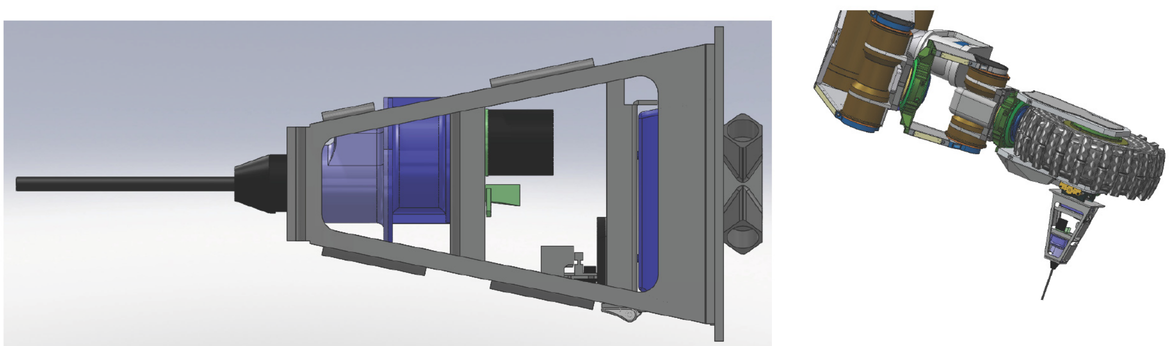
Figure 13: Schematic comparison of off-the-shelf electronic control system with the ATHLETE electronics design.

Several bit change scheme concepts for a separate drill bit holder were brainstormed. The two most practical schemes are discussed here. The first scheme is a passive scheme that requires no actuation beyond the rover limb being able to move the drill tool. The bit is retrieved simply by rover pressing the chuck against it. To remove the bit, the rover uses a bearing-mounted component to press against and push up the chuck collar, while a coupled linkage mechanism provides the force that pulls the bit from the chuck.

A second actuated scheme works in a similar way, using linear actuators such as solenoids to perform the functions of shifting the bearing-mounted component over for bit removal and of pulling the bit out of the chuck.

5 Conclusion

Design objectives for an ATHLETE rotary percussion drill tool were clearly defined. Using these objectives, the design process for creating a tool prototype was begun. A comprehensive design for the tool package structure was synthesized, with analysis performed to support it. Future work will include designing an outside cover for the tool as well as sizing fasteners for the structural joints. The electronic control system was also designed and a prototype was fabricated, resulting in a successful demonstration. Remaining work includes integrating the physical electronics with the mechanical design of the package. Finally, bit change mechanism schemes were explored and conceptualized. Further work on bit change mechanism would be to design, simulate, and eventually prototype a mechanism.



(a) Right view (b) On ATHLETE limb

Figure 14: SolidWorks renderings of rotary percussion drill tool design.

Acknowledgements

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A Load Case Stress and Displacement Plots from Finite Element Analysis

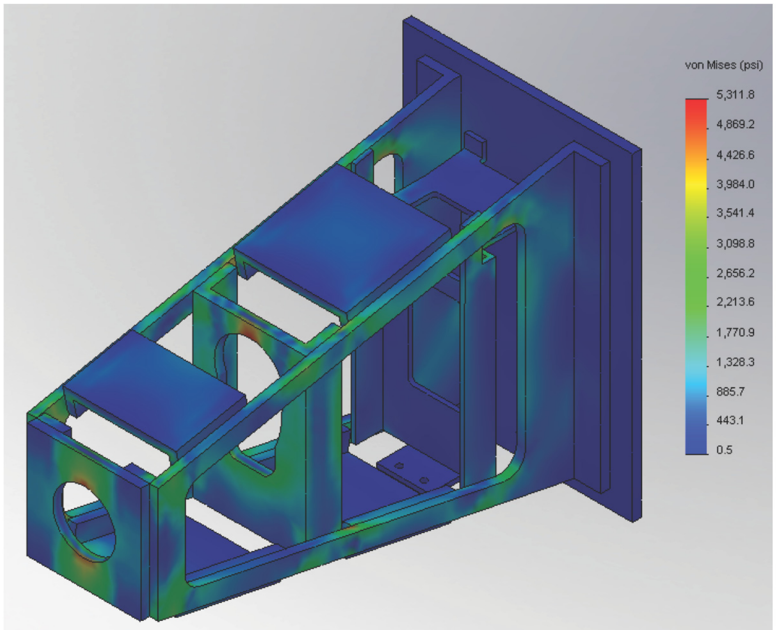

Figure 15: Load Case # 1: Static von Mises Stress Plot

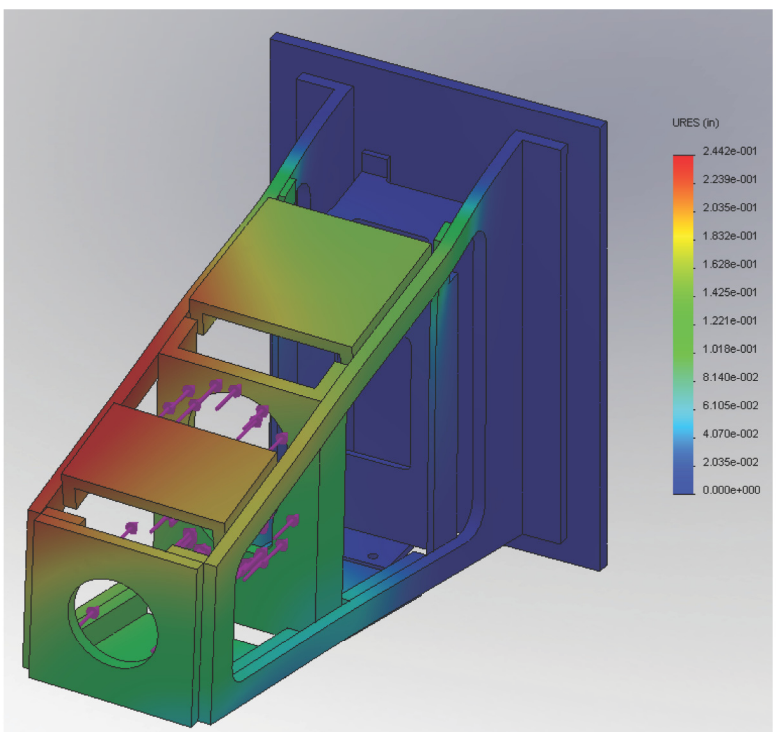

Figure 16: Load Case # 1: Buckling Displacement Plot

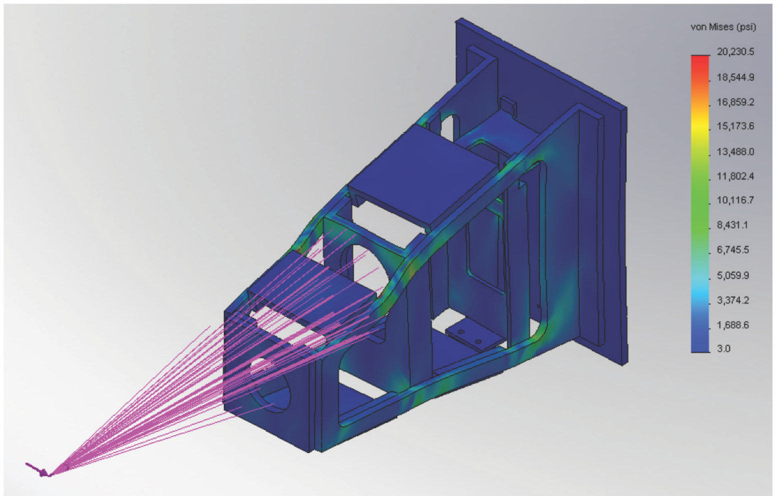

Figure 17: Load Case # 2: Static von Mises Stress Plot

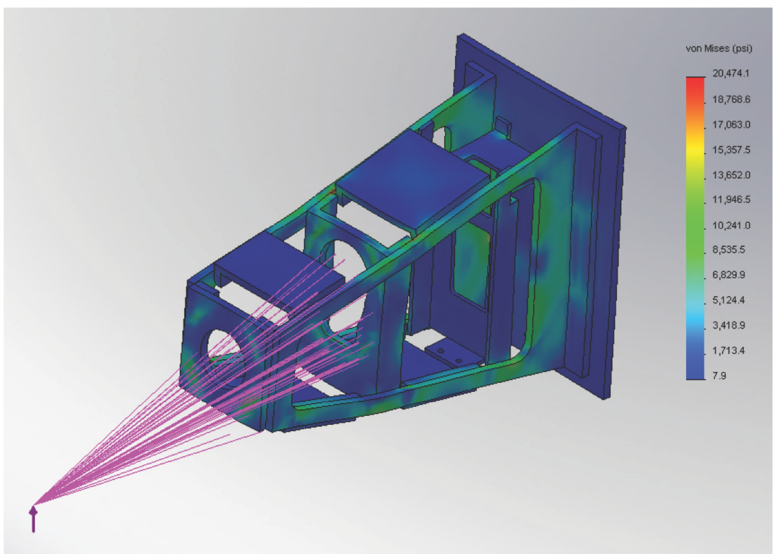

Figure 18: Load Case # 3: Static von Mises Stress Plot

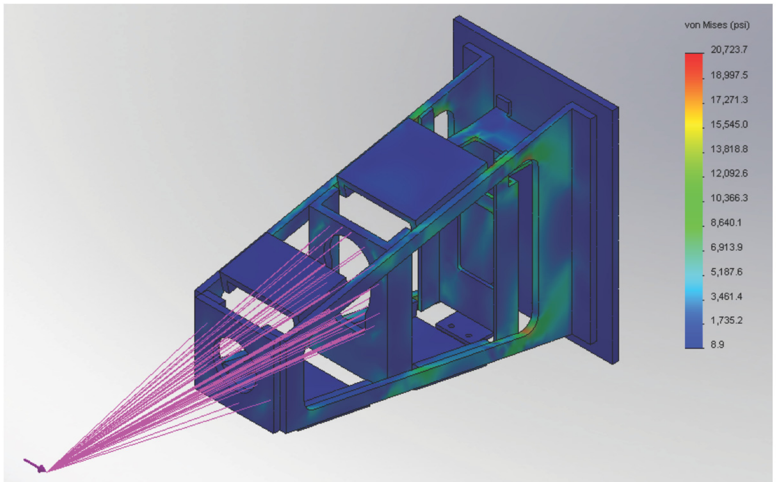

Figure 19: Load Case # 4: Static von Mises Stress Plot

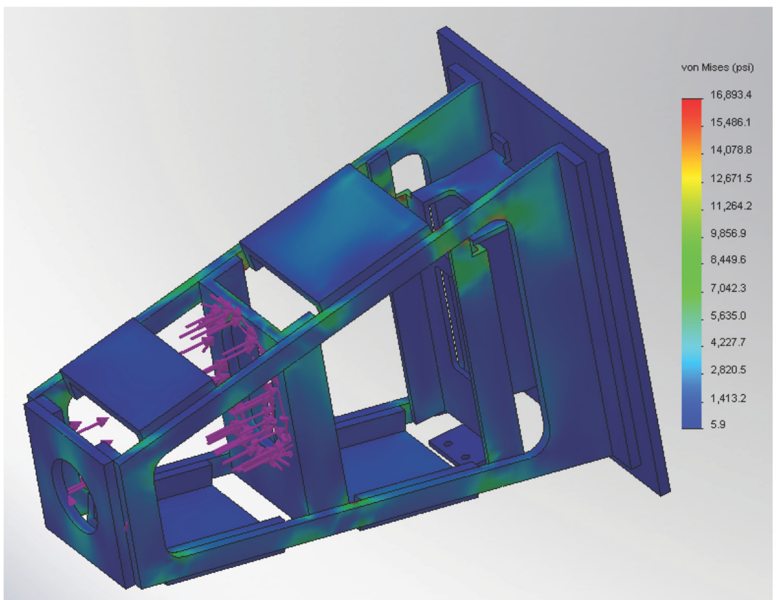

Figure 20: Load Case # 5: Static von Mises Stress Plot