Ball Aerospace | 2020 White Paper

Miniaturized Tethered Braking System

University of Colorado Boulder
Mechanical Engineering
Design Center Colorado

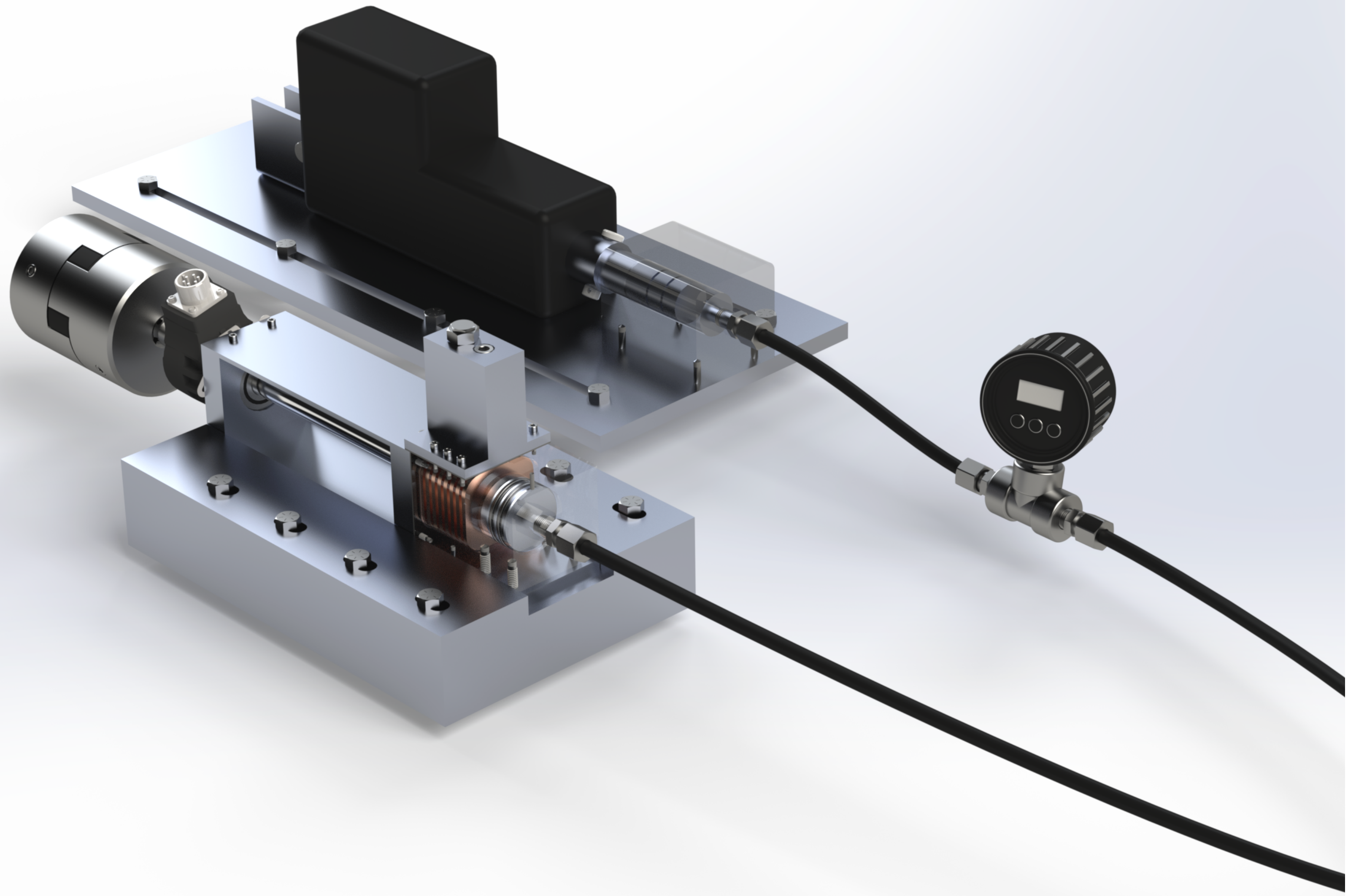

TABLE OF CONTENTS

03 EXECUTIVE SUMMARY

Our Mission

The Miniaturized Tethered Braking System (MTBS) is an electronically actuated, hydraulic-powered precision braking system capable of stopping a tethered 50-lb projectile traveling upwards of 270 mph within a fraction of a second. Our team has produced a design capable of satisfying a series of design specifications. The critical driving specifications are as shown below.

Design Specifications:

1. *MTBS shall allow the braking of a tethered 50-lb projectile at a maximum distance of 600 feet within 6 seconds.*
2. *MTBS shall be length-selectable by operator in 100-foot increments.*
3. *MTBS shall brake within ± 1 foot for every 100 feet of tether released.*
4. *MTBS shall be within a total volume of 95 cubic inches.*
5. *MTBS should be within a 12 inch by 2.85 inch by 2.75 inch envelope.*

For our MTBS design, we developed a braking method that is derivative of a wet friction clutch, often found in motorcycles. We accomplished our braking through an alternating series of splined steel and sintered bronze discs designed to disperse frictional braking forces onto a shaft coupled with a test apparatus provided by Ball Aerospace. The energy dissipated is characterized by rotational energy of the flywheel on the test apparatus. After the MTBS and test apparatus shafts are coupled together, the MTBS can start the braking procedure. This shaft contains a spool around which a tether that attaches to the projectile is captured. In order to compress the discs together, and thus brake the rotating shaft, we implemented a hydraulic system with a linear actuator to generate the required force. The linear actuator, mounted to the bed of the test apparatus, will compress hydraulic fluid through a high-pressure hose forcing a cylinder head to compress the discs, beginning our friction braking process.

The team would like to thank Ball Aerospace for their support of this project and the opportunity to work together on the Miniaturized Tethered Braking System.

04

PROJECT BACKGROUND

Our MTBS must interface with the test apparatus constructed by Ball Aerospace. This test apparatus flywheel spins, storing rotational energy in a flywheel contained on the test apparatus. This rotational energy, through the principles of conservation of energy, is representative of the linear kinetic energy of a 50-lb projectile. The purpose of this test apparatus is to safely simulate the energy that the 50-lb projectile would possess without having to fire a projectile at unsafe speeds for a typical work environment.

This test apparatus, pictured in Figure 1, consists of a motor capable of spinning a shaft at a maximum of 3,500 revolutions-per-minute. As pictured, a flywheel is located on this shaft. As discussed above, one can quantify the rotational energy in the system and consequently determine the linear projectile equivalent speed. From this baseline, one can determine the time, deceleration, and braking force required to stop the projectile. This is accomplished by slowing down the tether spool on the MTBS. This would, in turn, slow the tether release rate, thereby stopping the simulated projectile.

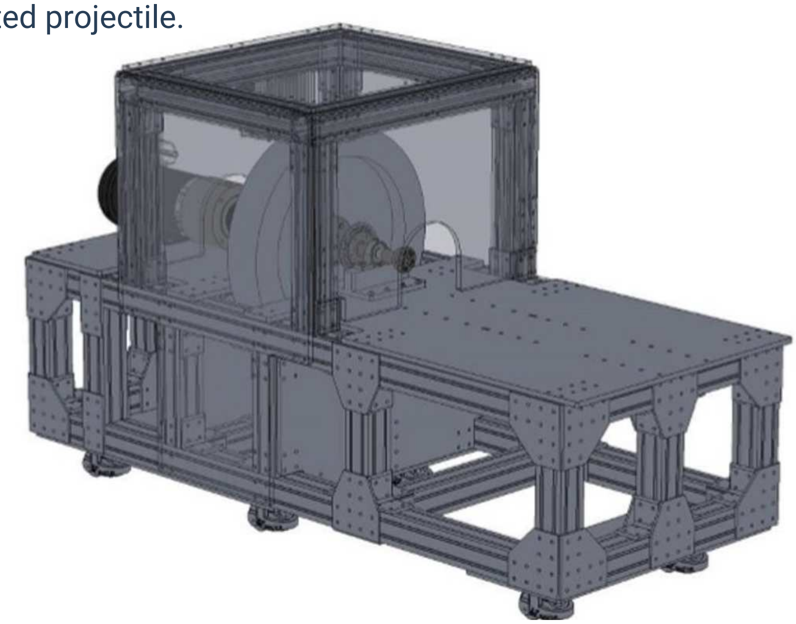

Figure 1: Ball Aerospace manufactured test apparatus pictured with flywheel.
The MTBS will be mounted on the plate to the right of the flywheel.

The motor can operate at a maximum of 3,500 rpm. This was defined by Ball Aerospace as the maximum energy condition. The total rotational energy of the flywheel is calculated using this maximum rotational velocity and a given moment-of-inertia for the flywheel. Thus, the team has designed the MTBS to dissipate and absorb the energy for this maximum energy condition. A maximum rotational velocity of 3,500 rpm possesses 160,000 J of energy. This amount of rotational energy is representative of a 50-lb projectile traveling in a straight line at an initial velocity of 270 miles per hour, or 400 feet per second (120 meters per second).

05 MTBS DESIGN COMPONENTS

Braking Structure

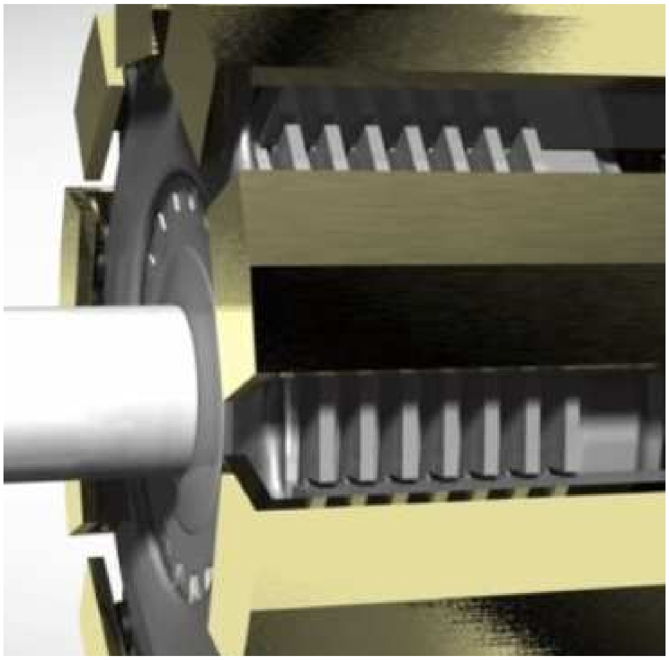

Figure 2: Motorcycle Clutch

The idea of our braking structure was based on principles of a motorcycle clutch, depicted in Figure 2. In a motorcycle clutch, a series of alternating discs—one rotating with a shaft and the other freely rotating—are compressed together when pressure is applied via the clutch. The rotating and free discs become rotationally matched as a result of compressive and friction forces. To brake using this concept, pressure will be applied via a piston cylinder. Instead of meshing a rotating and free spinning set of discs, we are meshing splined, spinning steel discs with rotationally locked sintered bronze discs. To help spread out the heat of the system, the discs are encased in oil to assist in absorbing and dissipating the heat.

Friction Interfaces

The friction braking discs are made of a sintered bronze friction material, designed for lubricated applications. The friction coefficient between the steel and the bronze material is 0.08-0.12. By taking the lowest coefficient of friction, for a higher factor of safety, we determined the optimized total number of discs from the force applied by the linear actuator. After balancing structural integrity and required input force, we elected to use 17 total discs: 8 steel discs and 9 friction discs.

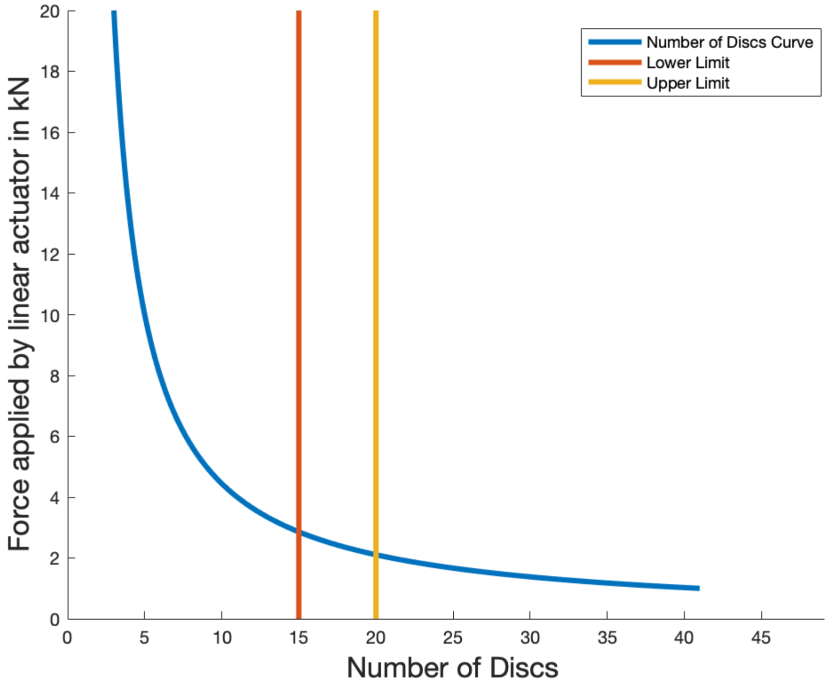

Figure 3: Required Force vs Total Number of Discs

06 MTBS DESIGN COMPONENTS (CONT.)

Braking Forces

Splined steel discs match the splines of the shaft and rotate with the shaft. Between each of the splined discs is a rectangular sintered bronze friction disc. These discs are rotationally-locked by the inside profile of the disc housing. A cylinder head is enclosed behind the discs in the housing. Using a hydraulic system, pressurized fluid pushes the cylinder into the discs. This pushes the steel and friction discs together slowing rotation of the splined discs on the shaft, thus braking the flywheel.

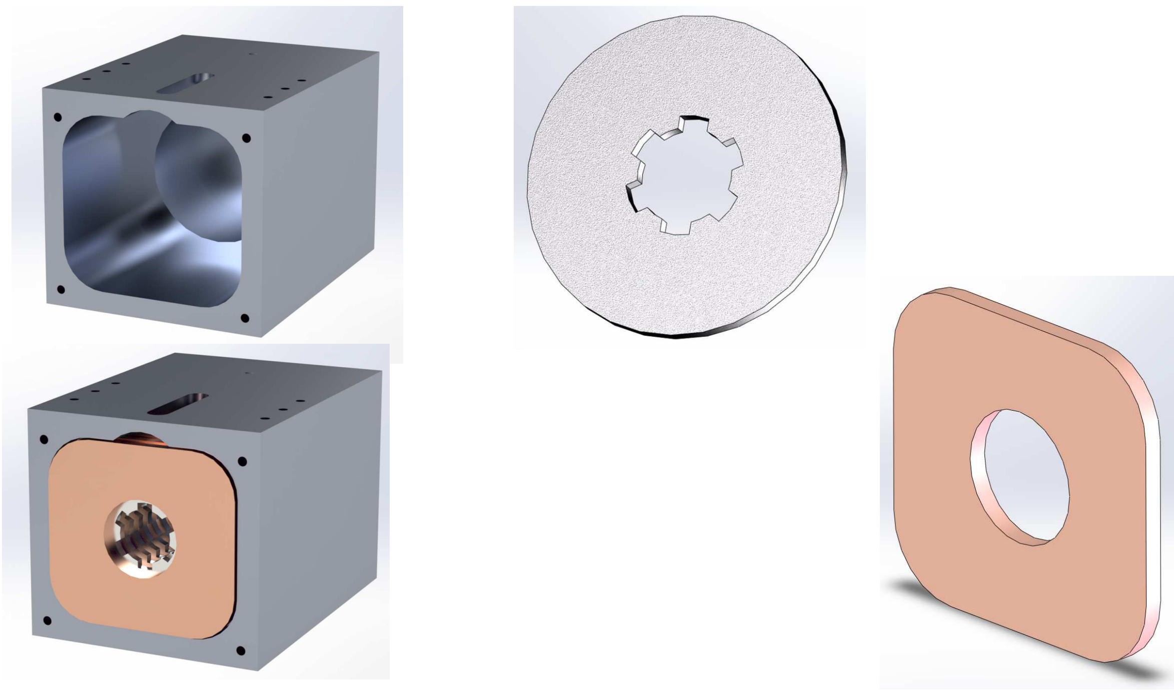

Figure 4: Disc housing and assembly

Hydraulic System

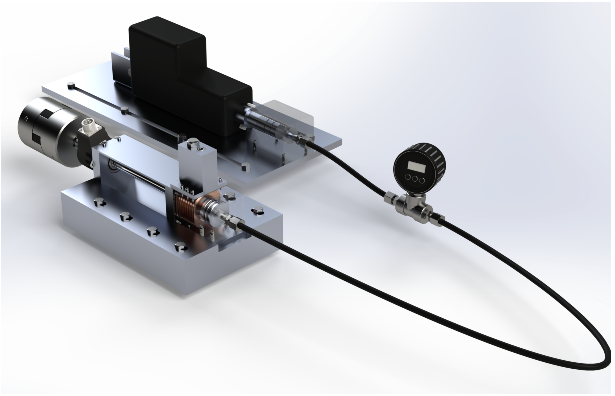

Figure 5: MTBS with Hydraulic System

To achieve the 1200-lb force required to compress the discs, a linear actuator axially translates hydraulic fluid through a high-pressure hose forcing a cylinder head to push the discs together. The connection of the hydraulic line allows the MTBS to maintain a profile of less than 95 cubic inches since the linear actuator can be located remotely, increasing safety. Finally, this hydraulic system allows the MTBS to gain a further mechanical advantage of 1.96:1 as a result of synchronous pressure being applied across different sized piston cross sections.

MTBS CHALLENGES

Expansion Tank

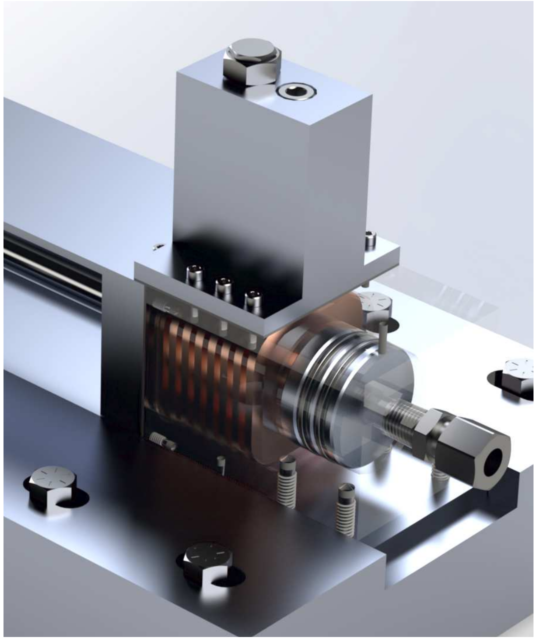
Figure 6: The expansion tank

With high friction from the discs, there are large thermal temperature spikes in the disc housing, that transfers to the rest of the MTBS. One way to dissipate heat inside the housing is to lubricate the discs with high-temperature chain oil. Although this oil will not reach the flash point, we expect 20% expansion in the oil at our maximum energy condition. As a result of this expected expansion, a tank is fastened to the top of the housing that could be located remotely, such that our design envelope is maintained. This expansion tank is designed to accommodate the oil expansion over a 300°C change. Two ports are added to the top of the tank. One port is sealed and the other is for a 1/4" diameter breather vent. The sealed port can be removed for the addition of inert nitrogen or carbon dioxide or the insertion of a thermocouple into the tank for monitoring the thermal profile. A gasket is placed between the tank and the top of the MTBS to prevent any leakage of oil.

Bearings, Gaskets, and Seals

With high pressure from the hydraulic system and thermal expansion/heat from the friction discs being compressed, we risk fluid leakage. To combat the oil and hydraulic fluid leakage, specialized bearings, gaskets, and seals were added. Due to potential misalignment between the MTBS and the flywheel test apparatus, we used bearings that allow for minor shaft deflection. We expect loading to be primarily axial, but we do expect some radial load from temperature expansion in the shaft. With a maximum temperature change of 300°C, we see a maximum change in outer shaft diameter of 0.0019 inches. Our team designed neoprene gaskets to insert and compress around our metal-metal interfaces to prevent leakage.


Figure 7: A cylinder head sealing O-ring


Figure 8: A sealing gasket located between the disc housing and the expansion tank

08

PROJECT CHALLENGES

Throughout the development of the MTBS, our team encountered several challenges. Chiefly, the four design constraints that we identified as being critical were dissipating 160 kJ of energy, a tight (±1%) braking distance tolerance to comply with, a short time window of under 6 seconds to complete the process, and a small design envelope of 95 cubic inches to fit the MTBS within. Finally, the team had to readily adapt our workflow and project priorities during the latter portion of the MTBS development to ensure that these operational objectives of the project remained uncompromised in the midst of the COVID-19 pandemic.

The maximum energy condition of the braking system requires the MTBS to dissipate 160 kJ of energy primarily as heat. With an interior volume of less than 22 cubic inches, the disc housing is where all the heat is initially transferred. Consequently, the team went through several design iterations and thermal analyses of various different heat transfer options before settling on the oil-filled housing option described on pages 6-7 of this paper.

The 1% error in braking distance drove requirements for component selection and the team's controls/feedback implementation. For example, at our maximum energy condition with the shortest braking distance selection of 100 ft, we would have a projectile traveling at 400 ft/s, indicating the MTBS must complete the entire braking process in approximately 0.50 seconds.

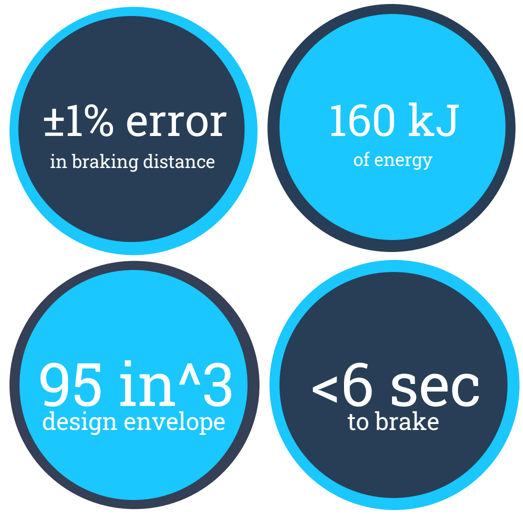

Figure 9: Four key design constraints for the MTBS

The six second time-frame to complete the braking process holds across all braking profiles. Our team designed profiles for every operative condition such that any speed could be accommodated for the selected length of 100 to 600 ft in 100 foot increments.

The 95 cubic inch volume constraint was the most difficult constraint to meet. By keeping this driving constraint at the forefront of our design decisions, the team was able to stay within the design envelope through the use of clever methods such as remote hydraulic force generation.

Finally, the rapid onset of COVID-19 created notable challenges in completing the MTBS development without compromising operational quality. The team worked diligently and put an emphasis on creating detailed plans and establishing clear communication channels in a continuously changing project landscape to deliver a functioning product for Ball Aerospace.

09 LONG TERM IMPACTS

The development of the MTBS was an invaluable experience for our team of young engineers. The MTBS was an opportunity for the team to go through the design process in great depth for a long-term project with a leading industry partner. From the moment we identified the specifications the MTBS shall satisfy, to preparing to deliver the product to our client, the insights we have been able to take away will undoubtedly prove essential in our future careers.

Additionally, the nature of this open-ended design project meant that there was no single correct answer to the question of the best way to design a precision braking system. As we discovered during the early phases of our project, we could prove that certain methods were more effective than others, but there was not a correct answer to which braking method we should select or which hydraulic fluid to utilize, or even what material to make our friction braking discs out of.

The opportunity to do this research, examine material properties, and reach out to vendors is an essential tenant of what engineering is—the ability to make informed decisions and understand the cascading effects of those choices is a skill that every team member now possesses.

As discussed, this project was not without its internal design challenges and surprising external circumstances. However, this team's optimism and unyielding commitment to producing an exceptional project led to the success of the MTBS. At the end of the project, the team is confident that we have created a functional product that is capable of satisfying every specification we set out to accomplish for our Senior Design capstone project.

Thank you for your time. If you have any questions about our project, please do not hesitate to reach out to the team members at the contact addresses specified below.

> "The ability to make informed decisions and understand their cascading effects is a skill that every team member now possesses."

The team would like to extend a special thanks to the following people:

- Jordan Shimonek and Luke Stahler, Ball Aerospace
- Daria Kotys-Schwartz and Julie Steinbrenner, Design Center Colorado
- Gabe Rodriguez, Danny Straub, Sean Sundberg, Program Assistants
- Tom Wilke, CU Boulder
- Greg Potts and Chase Logsdon, Design Center Colorado
- Shirley Chessman and Lauren Wheeler, Design Center Colorado
- Shalom Ruben, CU Boulder Mechanical Engineering
- Our team pets and morale leaders: Ellie, Gus, Beans, Lucky, Moose, Yoki, and Penny

TEAM BIOS

Matt Pipan - Project Manager

Matt is graduating with a BS of Mechanical Engineering with a minor in Engineering Management in May 2020. His post graduate plans include working for Ball Aerospace and eventually pursuing a program management role in the aerospace industry. Matt can be contacted at **Matthew.Pipan@colorado.edu**

Lauren Borchardt - Logistics Manager

Lauren is graduating with a BS of Mechanical Engineering with a minor in Space Studies in May 2020. She is a Certified Solidworks Associate and enjoys making CAD models come to life. She also has experience leading a team of students in an Engineering Work-space. Lauren is actively seeking employment opportunities and can be reached at **303-895-1440 / Lauren.Borchardt@colorado.edu**.

Alex Patterson - Financial Manager

Alex is graduating with a BS of Mechanical Engineering in May 2020. Alex has a vast working background in industrious positions as well as maintaining his own woodworking company over the past three years. Alex is actively seeking employment opportunities and can be contacted at **970-518-8601 / Alex.Patterson@colorado.edu**.

Altan Guc - CAD Engineer

Altan is graduating with a BS in Mechanical Engineering and a minor in applied mathematics. Altan is a Certified SolidWorks Mechanical Design Associate and has been using SolidWorks for computer aided design for 2 years. Altan has worked with a wide variety of teams to deliver successful final products. Altan is actively seeking employment opportunities and can be reached at **720-891-6713 / Altan.Guc@colorado.edu**

Patrick Burke - Systems Engineer

Patrick is graduating with a BS of Mechanical Engineering with a minor in Business and a certificate in Engineering Leadership. He has worked at a Test and Development and manufacturing sites for Intel, Patrick has experience in dealing with large facilities systems that are necessary for a factory to operate. Patrick is actively seeking employment opportunities and can be contacted at **719-339-5481 / Patrick.Burke-1@colorado.edu**.

Sebastian Alexander - Test Engineer

Sebastian is graduating with BS of Mechanical Engineering in May 2020. Through applied research experiences in CU Engineering labs he has developed experience in the designing, building, and executing of experimental apparatus and procedures. With an interest in mechatronics, his ultimate goal is to design rovers for space exploration. Sebastian is actively seeking employment opportunities and can be reached at **202-230-8967 / Sebastian.Alexander@colorado.edu**.

Parker Davis - Manufacturing Engineer

In academic and professional settings, Parker has shown his manufacturing aptitude, as well as engineering design knowledge across a wide portfolio of projects including configuring a welding robot, redesigning parts and fixtures, modifying tools, and teaching manufacturing techniques while working as a projects course TA and a CAD class shop assistant. Parker is actively seeking employment opportunities and can be contacted at **203-444-6047 / Parker.J.Davis@colorado.edu**.

Alex Patterson, Lauren Borchardt, Altan Guc, Matt Pipan, Patrick Burke, Sebastian Alexander, Parker Davis