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Capstone Design Project

Faculty of Engineering – McMaster University – Undergraduate Studies
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MA02 Final Report: Baja SAE Wheel Force Transducer

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Executive Summary:

The McMaster Baja Racing Team has not previously had an effective method for measuring the forces experienced by their car. Instead, the team has always employed inaccurate force estimations to design automotive components that either fail prematurely or are overdesigned. Though using a wheel force transducer (WFT) is the obvious solution in quantifying these forces and moments, the limited suppliers of these instruments sell them at a cost upwards of $75,000 USD. Not only does this cost exceed the annual budget of the Baja Team, but commercial WFTs are often too large to fit within the team's rims and have a weight comparable to the car's unsprung mass.

In response, Group MA02 set out to create an affordable WFT (using only the $500 CAD provided by the department) that is compatible with the McMaster Baja car. The purpose of this report is to not only document all work and processes for the Department of Mechanical Engineering but serve as a reference for the McMaster Baja Team. It is the hope of Group MA02 that the Baja Team will continue to revise and improve upon the completed WFT (and validation process) detailed in this report.

As a result, this report details background research, problem analysis, and the design selection process that was employed to meet the Baja team's design constraints of a WFT weighing less than 6lbs, having a minimum fast fracture FOS of 1.25 (Von Mises), and having a fatigue life of 32 working hours at an RPM of 466.67. This report then goes on to discuss how the selected final design, as well as key FEA studies, promise a fast fracture FOS, fatigue life, and mass that surpass the expectations/constraints outlined by the Baja Team.

Additionally this report covers the design of the DAQ system and why (and how) their custom designed PCB utilizes a Teensy 4.1 microcontroller (sampling rate of 1kHz) with six strain gauge Wheatstone bridges to produce 1x6 strain vectors denoted as $\overline{\boldsymbol{S}} = \left[S_{F_x}, S_{F_y}, S_{F_z}, S_{M_x}, S_{M_y}, S_{M_z}\right]$. More importantly this report will also review how Group MA02 was able to procure, manufacture, and integrate both the WFT body and DAQ system while remaining within their overall budget of $500 CAD.

With a completed and assembled WFT body and DAQ system, MA02 then designed and manufactured a calibration jig and validation process. This report discusses how this was employed to create six calibration curves for the three force directions $(F_x,\ F_y, F_z)$ and the three moment axes $(M_x,\ M_y, M_z)$. The unique and creative modular design of the calibration jig, as well as its low cost and ability to interface with the Baja team's weld table, is also discussed extensively in this report.

Lastly this report contains results from WFT field tests, where the WFT was mounted onto the Baja car prior to it performing maneuvers such as sudden braking, driving over rail-ties, and launching off a ramp in a controlled environment. These readouts were subsequently overlaid with video footage of these maneuvers to better understand the time stamps of which forces and moments were experienced when.

Project Background:

McMaster Baja Racing is a student-run engineering team that designs, builds, and tests a new off-road vehicle each year. In order to design automotive components with a satisfactory life span (and avoid costly overdesign), the forces and moments experienced by each component (and by extension, the entire car) must be understood. Yet, the McMaster Baja Team has no effective method for measuring the forces experienced by their car.

Instead, all force deductions are based entirely off of estimations of impact speed, impact duration, and force direction found in team legacy documents. Not only is this method highly inaccurate, as discussed under "*McMaster Baja Force Deduction Methods*", but it also does not capture the variable loading conditions the car experiences when driven on an off-road course. Not surprisingly, many of the team's components fail prematurely or are overdesigned.

In the automotive industry, design and test engineers often make use of a data acquisition (DAQ) instrument mounted to a car's hub, called a wheel force transducer (WFT). In general, WFTs contain multi-axis force sensors that elastically deform with the transducer body. These sensors (often strain gauges) output electrical signals that are recorded and converted into three-axis forces and three-axis moments experienced by the wheel.

These previously unknown forces and moments can then be applied to a finite element analysis (FEA) study of the car to fully understand the stresses experienced by each component. In turn, this would revolutionize the design process for the McMaster Baja Team, allowing them to create components and assemblies that focus on optimizing weight savings, material cost, and machinability without having to worry about premature component failure.

As detailed extensively below in "*Problem Analysis*", there are ample reasons to as why purchasing a WFT would be impractical for the McMaster Baja Team. For one, the cheapest quote Group MA02 could obtain for a WFT was $75 000 USD, which is far larger than the team's entire annual budget. In addition to the majority of the WFTs being too large to mount to the Baja car's relatively small hub, many of them also had a mass comparable to the car's total unsprung mass. A large unsprung mass from a WFT would produce erroneous force and load readouts far beyond what the Baja car experiences without a WFT attached.

In turn, this capstone project aimed (successfully) to design, build, and calibrate a functioning WFT for the McMaster Baja Team. In addition to addressing the team's barriers in obtaining one, this project was completed in collaboration with the team, with the goal of the WFT being further developed and improved by them for years to come.

McMaster Baja's Current Force Deduction Method:

For this section, Group MA02 spoke with current and past McMaster Baja Team Captains and Suspension Team Leads. When asked about current methods for determining the forces the Baja car experiences; all leadership members agreed that there are virtually none.

Current force deductions are based entirely off of estimations of impact speed, impact duration and direction found in legacy documents. The current Team Captain (and previous suspension lead), *Grace Worfolk*, notes that not only is this method "entirely inaccurate but does not capture [the] variable loading conditions" that the car experiences on an off-road course. Even if the force experienced by a single wheel was estimated with some degree of accuracy, this would only be for a very specific case/ loading condition. The current estimated legacy forces experienced by a single wheel are listed in *Table 1*. Though these values may not be accurate, they are crucial as a starting point for validating potential designs with FEAs.

Table 1: Legacy estimations of forces experienced by a singular McMaster Baja Car wheel.

Measurement	Legacy Estimate
Max Tire Radial Load	1000lbf
Max Tire Lateral Load	500lbf
Cyclic force amplitude	100lbf

Several published papers document the variable loading that automotive parts endure. For example, *Dr. Reza* investigates the variable loading of automotive knuckles, a critical component of an automotive steering system [1]. By using a wheel force transducer, *Dr. Reza* was able to record and deduce the variable stress experienced by knuckles while test vehicles performed different maneuvers on a closed track. The results of this test, seen in *Figure 1*, were then used to estimate the fatigue life of the knuckles. Data such as this allows automotive designers to not only avoid overdesigning components, but also produce designs that have infinite lives or satisfactory finite lives.

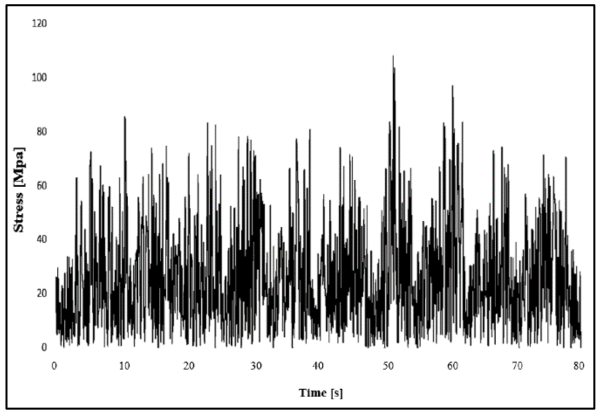

Figure 1: Example of varying Von Mises stress endured by an automotive component while a car performs various maneuvers [1].

However, these papers are not only for specific loading conditions, but are often focused on consumer cars. The design of Baja car components often differs from what is found in consumer vehicles and such components often undergo different loading conditions (i.e., off-road driving).

As a result, detailed in "*Project Problem Analysis:",* the McMaster Baja Team lacks the data acquisition tools to design components with a satisfactory life cycle without encountering costly overdesign. Overdesign is a major concern for the McMaster Baja Team primarily because of their limited financial budget.

Grace Worfolk, current McMaster Baja Captain, noted that she "cannot guarantee any money for the R&D of a wheel force transducer" but stated "that [our group], being members of Baja, have access to the many current sponsors [that] McMaster Baja uses". In the past, these sponsors have not only provided stock material, sensors, and DAQ systems, but also the use of their manufacturing tools and machines, entirely free of charge.

Social, Environmental, & Financial Factors:

As discussed above, the goal of this capstone project is two-fold: one, to address the McMaster Baja Team's barriers in gaining access to a WFT (particularly the financial aspect), and two, creating one that exceeds the length of this course and is used (and revised) by the team in coming years.

At first glance, it may be difficult to understand what social and financial factors this project addresses, as it does appear to be intended only for a small population of end-users (the McMaster Baja Team). In actuality, this project aims to address the social and financial discrepancies Canadian Baja teams face in comparison to American teams.

Figure 2: Michigan Tech Baja Team, among other American teams, have been able to secure WFTs from high-end sponsors [2].

It is no secret in the Baja SAE community that American schools are typically better connected in the world of industry and have a vastly larger budget than their Canadian counterparts. As previously mentioned, the cheapest quote Group MA02 could obtain for a WFT was $75,000 USD. Yet several American teams have access to, and already use, WFTs. For example, the Michigan Tech Baja Team employs a WFT (at no cost) from their sponsor Michigan Scientific Corporation as seen in *Figure 2* [2]. This is a common theme (exaggerated even more by American Ivy League schools) that leaves many Canadian teams at a very notable disadvantage.

One of the long-term intents of this project (beyond the Winter 2024 semester) is for the McMaster Baja Team to revise and tune this WFT design. It has been agreed among members of the team that they are to share the general WFT design and DAQ system with fellow Canadian teams. The goal of this is to minimize the aforementioned social and financial difference between Canadian and American teams by giving Canadian teams access to an affordable WFT design.

Though it seems uncompetitive to share novel designs with other teams, it is actually quite common in the Baja SAE community. The team who is first to create and implement such a novel idea is given credit where it gets used and is included in the sharing of other team's innovative ideas and designs.

As a result, it is a priority for this group (at no cost to the McMaster Baja Team) to share the high-level/general design of this WFT with other Canadian teams in order to alleviate the financial and social challenges Canadian teams face.

Background Research:

Measuring Principles of a Wheel Force Transducer:

Automotive vehicle wheels experience three-axis forces and three-axis moments. These forces are often referred to as the following in wheel force transducer design: the longitudinal force F_x, the lateral force F_y, the vertical force F_z, the heeling moment M_x, the twisting moment M_y, and the aligning moment M_z [3]. These forces and their orientation can be seen in *Figure 3* [4].

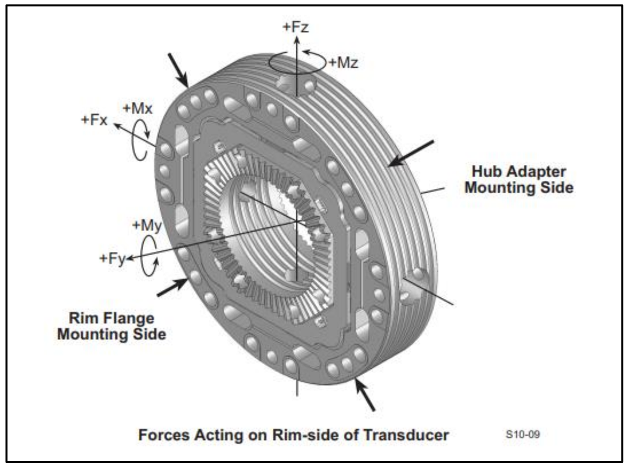

Figure 3: Standard wheel force transducer force and moment notation [4].

In general, wheel force transducers contain multi-axis force sensors that elastically deform with the transducer. These sensors (often strain gauges) output electrical signals that are recorded and converted into forces. This means that force vector ($\overline{\boldsymbol{F}} = \left[F_x, F_y, F_z, M_x, M_y, M_z\right]$) must be related to a recorded strain vector ($\overline{\boldsymbol{S}} = \left[S_{F_x}, S_{F_y}, S_{F_z}, S_{M_x}, S_{M_y}, S_{M_z}\right]$) through a 6×6 matrix denoted as C, where $\overline{\boldsymbol{S}} = C \cdot \overline{\boldsymbol{F}}$. *Dr. Lihang Feng* suggests that a self-decoupled elastic body with a diagonal matrix C is the primary target in WFT design [3].

Note that *Feng's* "easy-to-understand design procedure - including [a] conceptual design" will be discussed extensively under "*Literature Review of Dr. Feng's Open-Source Wheel Force Transducer"* [3].

Existing Solutions:

As detailed under "*McMaster Baja's Current Force Deductions Methods:*", WFTs are a necessity for major automotive groups. By gaining an understanding of the forces experienced by their vehicles, they are able to avoid overdesign and ensure that components have satisfactory life cycles (whether that be infinite or finite).

As a result of this very specific market demand, almost all existing solutions of commercial products are targeted towards major automotive manufacturers. In order to better understand the feasibility (or lack thereof) of the McMaster Baja Team simply purchasing a wheel force transducer, Group MA02 reached out to two of the most well-known companies in the market – *MTS Systems Corporation* and *Michigan Scientific Corporation*.

Both companies responded with specification sheets along with pricing quotes for their existing products that best suited the needs of a Baja vehicle.

MTS Systems Corporation:

As suggested by the group's contact at *MTS*, the *SWIFT 10T* wheel force transducer is the most compatible for a Baja SAE car. *Figure 42* (see "*Appendix A – Wheel Force Transducer Quotes:*"), an informal quote from *MTS,* highlights the high cost ($110 000 USD) of their smallest and cheapest WFT. This quote is characteristic of the price for most WFTs and is a cost that is vastly outside of the range of affordability for the McMaster Baja Team.

Additionally, their specification sheet (highlighted in *Figure 44* under "*Appendix B – Wheel Force Transducer Specification Sheets:"*) depicts a solution that is overdesigned for the needs of a Baja vehicle. For example, their maximum speed of 250kph and RPM of 2200 is far above the top speed of the Baja car (roughly 45kph).

Lastly, a WFT with a specified weight of 12.8lbs causes concern to the McMaster Baja's suspension sub-team. With an unsprung vehicle mass of about 60lbs, a 12.8lb transducer would wildly affect the car's characteristics, handling, and loading. The resulting force readouts would be larger than what the car experiences without a WFT and ultimately would still cause the McMaster Baja Team to overdesign parts.

Michigan Scientific Corporation:

The contact at Michigan Scientific suggested that the *LW25* wheel force transducer is their most compatible option for a Baja car. However, much like *MTS*, the quote, pictured in *Figure 43 (*see "*Appendix A – Wheel Force Transducer Quotes:*"), depicts a high starting price of $75 000 USD. This quote is on the lower end of commercial WFTs but is still unaffordable to the McMaster Baja Team.

The McMaster Baja suspension sub-team notes that the listed weight of 3.2lbs (see *Figure 45* under "*Appendix B – Wheel Force Transducer Specification Sheets:"*) is a more acceptable transducer weight for their applications. Being a quarter of the weight of the *SWIFT 10T*, force readouts from the *LW25* would be closer to what the Baja car experiences. Regardless of its mass and it being (or not being) overdesigned, the cost of either of these WFTs is by far the largest barrier for the McMaster Baja Team.

Literature Review of Dr. Feng's Open-Source Wheel Force Transducer:

As mentioned earlier, *Dr. Feng*'s paper, "Design and optimization of a self-decoupled six-axis wheel force transducer for a heavy truck", is one of few reputable sources that outlines an "easy-to-understand [DAQ] design procedure - with the aims of [creating] a universal-purpose self-decoupled transducer" [3].

Dr. Feng's work became an advantageous starting point for Group MA02 to create their own WFT. His concept (seen in *Figure 4*) comprises a strain plate (*image a) of Figure 4)* that includes eight elastic columns/spokes. Each spoke houses four strain gauges (one on each face) which are then arranged into six Wheatstone bridges (*image b) of Figure 4)*. Each Wheatstone bridge corresponds to one of the six force/moment axes ($\overline{\boldsymbol{F}} = [F_x, F_y, F_z, M_x, M_y, M_z]$) by recording the strain vector $\overline{\boldsymbol{S}} = [S_{F_x}, S_{F_y}, S_{F_z}, S_{M_x}, S_{M_y}, S_{M_z}]$[3].

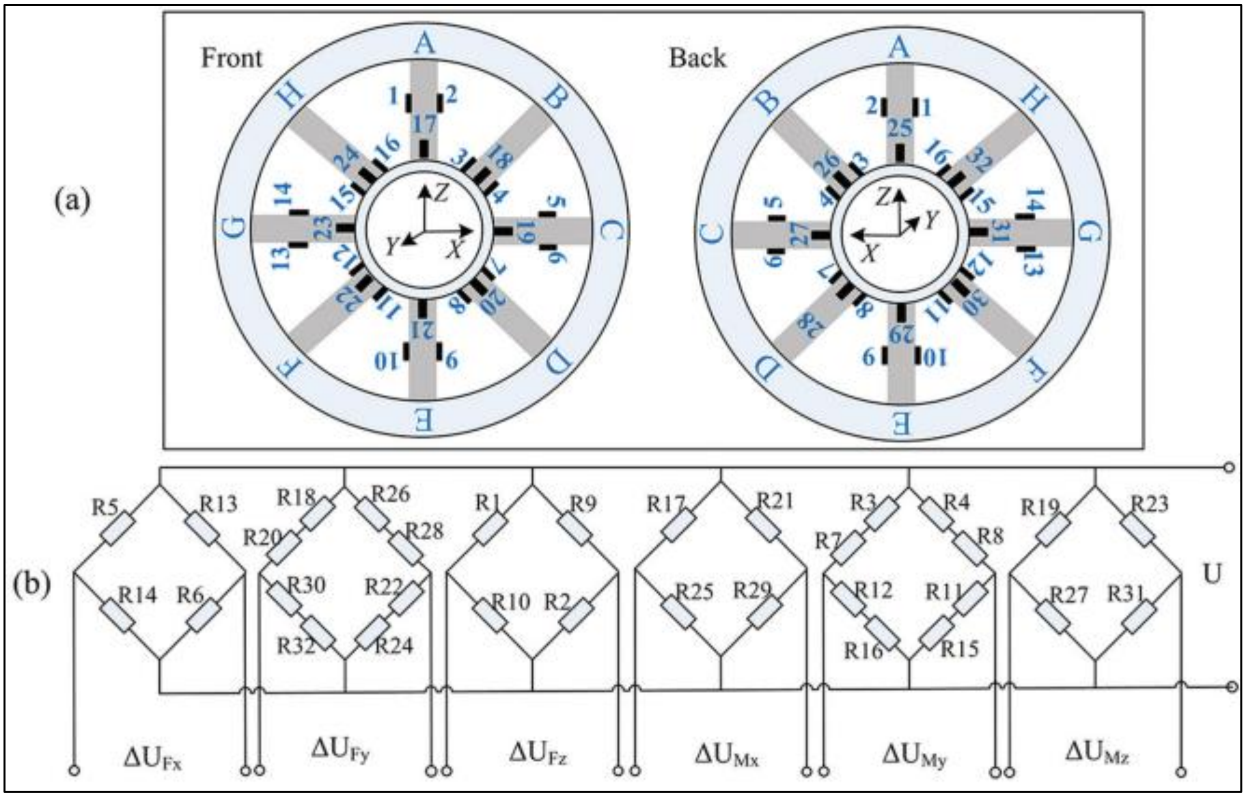

Figure 4: Feng proposes the use of a Wheatstone bridge (image b), for each of the six outputted forces/moments for a universal WFT [3].

Of course, this is only a broad/high-level design, and several other design decisions would need to be made by Group MA02. For example, a method to mount such a device onto the 2024 Baja car rim, while scaling it to an appropriate size to fit, would still need to be decided upon. MA02 would also need to deicide whether the Wheatstone bridges would be arranged on the PCB or be hardwired together. Additionally, a way to convert the strain vectors to the desired force vectors (readouts) would still need to be thought of.

Feng's paper suggests creating a 6×6 matrix which he refers to as compliance matrix (C) to calculate the force vector ($\overline{\boldsymbol{F}}$) using the recorded strain vector ($\overline{\boldsymbol{S}}$). This relationship can be seen in *Equation 1,* as well as a plausible compliance matrix, shown in *Figure 5,* to deduce force readings [3]. It is important to note that this is specific to the eight-spoke design published by *Feng* - the compliance matrix is based not only on the physical geometry of the strain plate, but also the number of strain gauges used, their placement, and connection, as seen in *Figure 4.*

$$\overline{\boldsymbol{S}} = C \cdot \overline{\boldsymbol{F}} \qquad Equation\ 1$$

$$Where\ \overline{\boldsymbol{F}} = [F_x, F_y, F_z, M_x, M_y, M_z]\ and\ \overline{\boldsymbol{S}} = \left[S_{F_x}, S_{F_y}, S_{F_z}, S_{M_x}, S_{M_y}, S_{M_z}\right]$$

$$
\begin{aligned}
C_{1j} &= 0.25(\varepsilon_5 + \varepsilon_6 - \varepsilon_{13} - \varepsilon_{14})_j, && j = 1, \ldots, 6 \\
C_{2j} &= 0.125(\varepsilon_{18} + \varepsilon_{20} + \varepsilon_{22} + \varepsilon_{24} - \varepsilon_{26} - \varepsilon_{28} - \varepsilon_{30} - \varepsilon_{32})_j, && j = 1, \ldots, 6 \\
C_{3j} &= 0.25(\varepsilon_1 + \varepsilon_2 - \varepsilon_9 - \varepsilon_{10})_j, && j = 1, \ldots, 6 \\
C_{4j} &= 0.25(\varepsilon_{17} + \varepsilon_{29} - \varepsilon_{21} - \varepsilon_{25})_j, && j = 1, \ldots, 6 \\
C_{5j} &= 0.125(\varepsilon_3 + \varepsilon_7 + \varepsilon_{11} + \varepsilon_{15} - \varepsilon_4 - \varepsilon_8 - \varepsilon_{12} - \varepsilon_{16})_j, && j = 1, \ldots, 6 \\
C_{6j} &= 0.25(\varepsilon_{19} + \varepsilon_{31} - \varepsilon_{23} - \varepsilon_{27})_j, && j = 1, \ldots, 6
\end{aligned}
$$

Figure 5: Plausible compliance matrix specific to Feng's eight spoke design [3].

Problem Analysis:

Feng highlights the importance of a group, such as the McMaster Baja Team, having access to a WFT, as it is near impossible to determine applied loads without a wheel force transducer when "road conditions include rough sandstone, tidal flats and drifting terrain" [3]. This section details the many unique problems and design constraints that must be considered when creating a WFT as well any specific design objectives requested by the client – the McMaster Baja Team.

Desired Outputs:

As discussed in detail in "*Measuring Principles of a Wheel Force Transducer:",* it is industry standard that a WFT that can provide six force/moment measurements as seen in *Figure 3*: the longitudinal force F_x, the lateral force F_y, the vertical force F_z, the heeling moment M_x, the twisting moment M_y, and the aligning moment M_z [3]. The McMaster Baja Team has requested that this WFT produces the same outputs/readings.

How the data is collected is based entirely off the selected DAQ System. Regardless of how collection method, Group MA02 and the McMaster Baja Team agree that the outputted data should be 1×6 strain vectors $\overline{\boldsymbol{S}} = \left[S_{F_x}, S_{F_y}, S_{F_z}, S_{M_x}, S_{M_y}, S_{M_z}\right]$ that can easily be related to a corresponding 1×6 force vector, as suggested by *Feng* [3]. As seen in the *"Concept Generation"* section, this strain data does not necessarily have to be captured with strain gauges and can use other methods such as Hall effect magnets. The data capturing method is discussed below in detail under *"Selection of DAQ System".*

Selection of DAQ System:

It is important to note that, before any other design constraint or problem can be addressed, a data collection method must be decided upon. This means that all generated concepts are uniquely based on how the data is collected. As seen in *Figure 6,* the design of the hardware system, as well as the physical WFT body, is entirely dependent on the selected DAQ method. For example, *Feng's* Wheatstone bridge in *Figure 4* is only applicable to an eight-spoke design that utilizes strain gauges [3]. Regardless of which data collection method is employed, it is important that the data is collected, processed, and presented into 1×6 strain vectors ($\overline{\boldsymbol{S}} = \left[S_{F_x}, S_{F_y}, S_{F_z}, S_{M_x}, S_{M_y}, S_{M_z}\right]$). Because of this, Group MA02 favours design concepts that mimic that of *Feng's* [3], as this course's timeline is likely too short to develop a novel WFT data collection method.

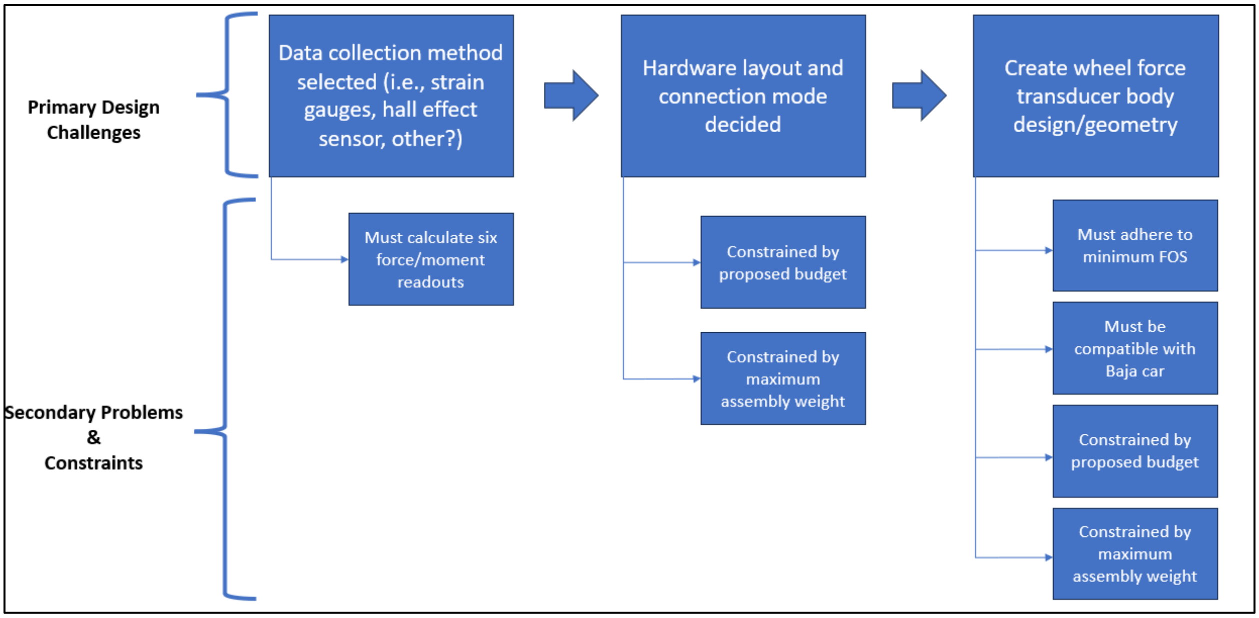

Figure 6: Broad overview, showing that every major design challenge and decision is based on the selected data collection method.

Calibration:

It is common knowledge that any functioning measurement instrument must be calibrated to verify its accuracy and precision. A WFT that is not properly calibrated would produce force and moment values that are either higher or lower than reality. If larger, the McMaster Baja Team would continue to produce overdesigned components that negatively effect their car's budget, weight, and manufacturing time. If smaller, the team would produce components that fail prematurely from fast fracture or fatigue life failure. Therefore, calibrating a WFT is the most important step once a design is finalized.

In order to calibrate the WFT effectively, a calibration jig will be used to apply a measurable force in each of the three primary axes. Additionally, the jig will produce a measurable moment about each of these three primary axes. Group MA02 has taken a particular interest in *Kebede's* simple, functional, and cost-effective jig, seen in *Figure 7* [5]. This method can apply all necessary forces and moments through a cable that suspends known weight (force) from the WFT body. Pulleys are used to direct this force. *Figure 7* shows four of the six force and moment orientations required [5].

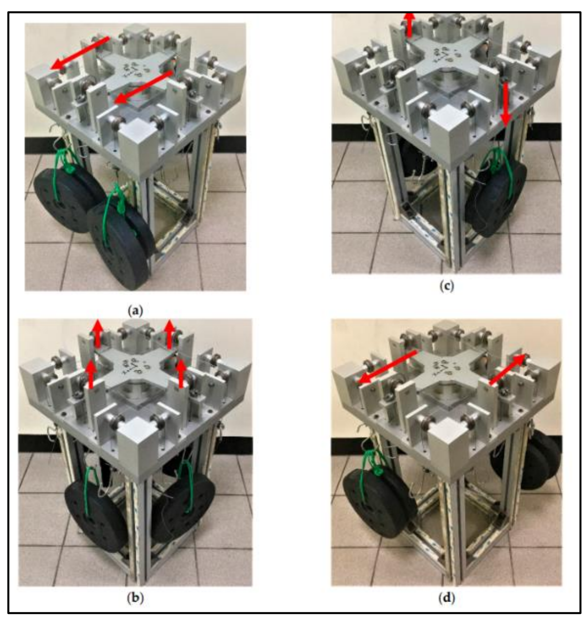

Figure 7: Cost effective method of calibrating a wheel force transducer in a controlled environment [5].

For each force and moment axis, weights will be added in linear increments. As a result, a successful calibration curve (Y-axis recording ADC voltage, X-axis recording mass) would appear to be linear. As explained in "*Design Objective & Constraints",* it is the goal of Group MA02 that each of the six calibration curves for the six moment and force axes have a Pearson correlation coefficient equal to or greater than 0.9 ($r \geq 0.9$). Though not perfectly linear, (and, as a result, some error will be present in each axis) Group MA02 recognizes this as a tremendous achievement for the McMaster Baja Team's first iteration of a WFT.

Fast Fracture Factor of Safety:

The McMaster Baja Team requires all components to have a minimum fast fracture FOS of 1.25 using Von Mises criteria under the loading conditions of 1000lbf radial load and 500lbf lateral load applied to the rim of the car (see *Table 1)*. Additionally, the team requests that Group MA02 follow their process for assessing FOS. Each design is to be subjected to the loading specified above in a SOLIDWORKS FEA assembly where an FOS plot can be generated to determine a minimum FOS and highlight any areas of significant stress concentrations.

Fatigue Life:

When components are exposed to time varying loads over many cycles, they undergo fluctuating (alternating) stresses that can result in fatigue failure. Fatigue failure is an important consideration in design as an alternating stress that causes fatigue failure is often many magnitudes lower than the ultimate or even yield strength of the same material [6]. Through tests and subsequent collection of empirical data, S-N curves are created which show the lifespan for specific materials under an alternating stress. For example, in *Figure 8*, an S-N curve for UNS G41300 steel showcases a finite life region and an infinite life region. To find the lifespan of a designed component, one must first find the location and value of the most critical endurance limit (S_e). A component is within the infinite life region when its endurance limit (S_e) is less than the horizontal plateau of fatigue strength (S_f) for its specific S-N curve.

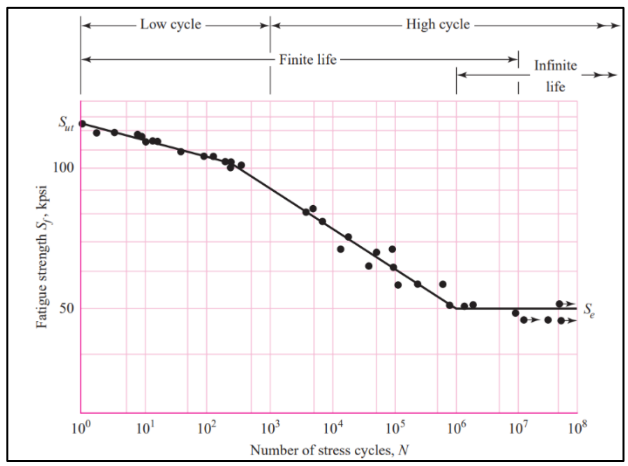

Figure 8: S-N diagram plotted from fatigue tests of UNS G41300 steel with an ultimate strength of 125kpsi [6].

A WFT is no exception to this rule. As a WFT spins on a vehicle's wheel, any surface under bending will fluctuate between tensile and compressive stress during each revolution of the hub. In addition, any axial component of stress will be superposed upon said bending moment during rotation.

Initial Fatigue Life Objective:

Upon writing of the SoW document in October 2023, the McMaster Baja Team requested that the fatigue life of the WFT body be infinite for a cyclic force amplitude of 100lbf (see *Table 1);* in other terms, $\sigma_{\max amp} < S_e$.

However, another major design objective in the SoW document was to keep the total mass of the wheel force transducer below 6lbs (see *"Total Mass"*). A large unsprung mass from a WFT would produce force and load readings largely above what the Baja car typically experiences when a WFT is not attached. These larger readings, deviating from the actual lower value, will counterproductively cause the team to overdesign their components – defeating the purpose of using a WFT.

During the design concept generation phase, each potential design was digitally modeled through CAD (see "*Concept Generation*"), allowing group MA02 to easily calculate the mass of each design with various material selections at the click of a button. It became very apparent that the only materials that allowed for a total mass under 6lbs were aluminum and titanium alloys. Given the project's strict budget, and that titanium typically has a higher density than aluminum, titanium was ruled out early on. This led to the conclusion that the only material that would be able to fit within the weight criteria, strength requirements, and budget, was aluminum.

Uncertainties/Issues of Initial Objective:

However, the issue arises when the fatigue life of aluminum is considered. Aluminum, unlike steel, has no plateau on it's S-N curve(s) and, as a result, has no endurance limit or "infinite region" as seen in *Figure 9* [7]. Because of this, Group MA02 had to decide whether between pursuing the objective of an infinite life WFT with steel and producing a WFT that met the maximum mass objective by using aluminum.

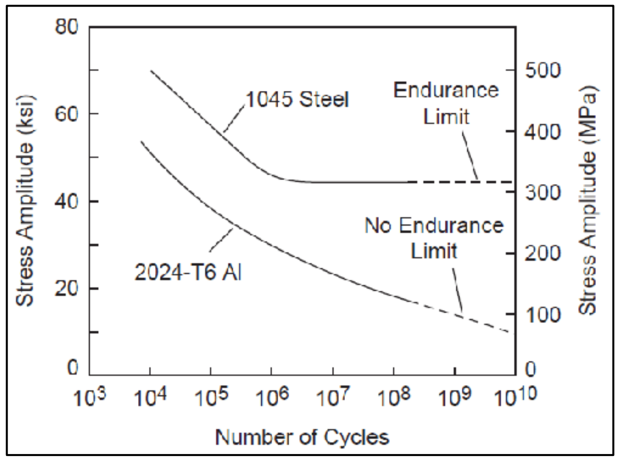

Figure 9: Comparison of steel vs. aluminum fatigue behaviour shows that aluminum does not typically have an infinite life region [7].

After several discussions, Group MA02 concluded that the mass objective was a more important design objective than having an infinite life. Again, a heavy WFT would produce larger force readings than what the car experiences without a WFT attached and, as a result, would lead to the McMaster Baja Team overdesigning components – defeating the purpose of a WFT.

Additionally, an objective for a long fatigue life can still be implemented for a WFT body made of aluminum. A life cycle of tens or hundreds of thousands of cycles will be satisfactory, as the McMaster Baja Team plans to only drive with the WFT for short periods of testing and would do so in a controlled environment as opposed to a lengthy endurance race.

Updated Objective:

The McMaster Baja Team leadership has agreed to change the infinite life objective to a minimum fatigue life of 32 hours. Again, legacy data outlined in *Table 1* will be used, which assumes the wheel experiences a cyclic force amplitude of 100lbf while running.

Group MA02 also assumes that the engine operates at a constant rotational speed of 2800 RPM with an overall gear reduction of 6.0 to both the front and rear wheels (without slipping). Simple math supports the fact that the WFT will experience 466.67 RPM. 466.67 rotations per minute, over the course of 32 hours, results in a total of 896,000 cycles. From the design choice of aluminum, the most commonly available aluminum alloy with the best mass-to-strength ratio is 7075-T6. From *Zainezhad's* empirical S-N curve of 7075-T6 (shown in *Figure 10*) [8], it is clear that the WFT must have an endurance limit below 240MPa in order to have a lifespan of 32 working hours.

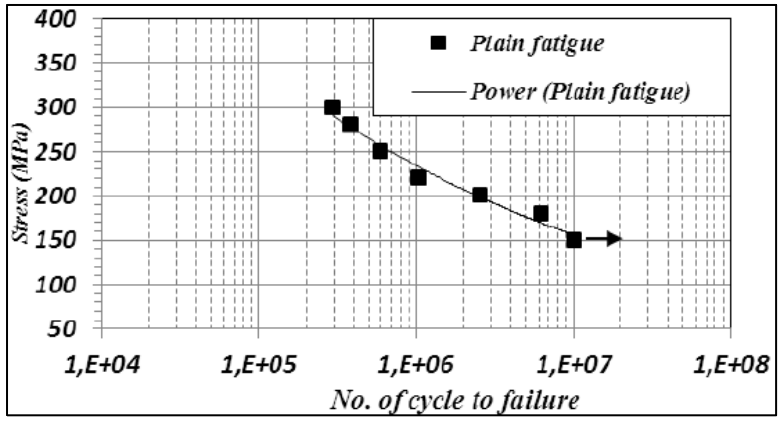

Figure 10: S-N curve for 7075-T6 shows that, in order to obtain roughly 900,000 working cycles, the endurance limit must be below 240MPa [8].

Therefore, the project's design objectives have been updated so that the WFT body no longer requires an infinite fatigue life, but rather 32 working hours or an endurance limit below 240MPa using 7075-T6 aluminum.

Total Mass:

The McMaster Baja suspension sub-team has made it known that the total unsprung mass of the vehicle is approximately 60lbs.

The mass of a WFT adds to the car's unsprung mass and negatively effects the handling, loading, and characteristics of the car. A large unsprung mass, from a WFT would produce force and load ratings largely above what the Baja car typically experiences when a WFT is not attached. These larger readings, deviating from the actual lower value, will once again cause the team to overdesign.

As seen under "*Appendix B - Wheel Force Transducer Specification Sheets*", *MTS's* recommended transducer has a mass of 12.8lbs. If the unsprung mass of the Baja car was divided equally between its four wheels (a total of 15lbs of unsprung mass per wheel), this WFT would nearly double the unsprung mass of the wheel it attaches to.

This is not surprising as WFTs are made almost exclusively for commercial vehicles. Commercial vehicles have an unsprung mass much larger than the Baja car and, as a result, are affected nominally less by the addition of the transducer's mass.

Because of this, the McMaster Baja suspension sub-team has laid out the design constraint of the WFT weighing less than 10% of the car's unsprung mass. This means the entire assembly (including hardware) will need to weigh under 6lbs.

Budget:

Initial Objective:

As detailed under "*Project Background*", two price quotes obtained from *MTS* and *Michigan Scientific* list their cheapest models being priced at $110 000 USD and $75 000 USD, respectively. Both, of course, are out of the price range for the McMaster Baja Team. Additionally, the McMaster Baja Team is not able to guarantee provision of any funding for the R&D of a wheel force transducer.

However, as discussed under "*Project Background*", Group MA02 does have access to the many sponsors of the McMaster Baja Team. Sponsors include MAGNA, Schaeffler, True Gear & Spline LTD., Unified Engineering, PCBWay, Mancor Industries, and many more.

These sponsors have previously provided and continue to provide the team with stock material which is one of the largest monetary costs associated with building the WFT body. Group MA02 is confident in its ability to source the material for the body at no charge through one of the many sponsors.

Additionally, PCBWay has already agreed to print all necessary PCBs for the project at zero cost and SOLIDWORKS has already provided all group members with free licenses to their platform including FEA.

If all machining is done by members of this group (at no monetary cost), stock is obtained for free from a sponsor(s), and PCBWay delivers on their promise, the group believes that the WFT can be designed and built using only the $500 CAD budget provided by the Department of Mechanical Engineering.

Uncertainties/Issues of Initial Objective:

One of the budget objectives highlighted in the SoW document was to spend $0 on WFT body stock by using a sponsor of the McMaster Baja team that would supply stock for free. As discussed extensively under "*Fatigue Life",* after several design iterations, Group MA02 decided on using 7075-T6 for the transducer body due to its high strength-to-mass ratio. The use of 7075-T6 is also reflected in the latest objective to have a WFT with an endurance limit below 240MPa for a fatigue life of 32 working hours.

However, in doing this, a new issue arose. After contacting several of the team's material sponsors, who were happy to provide stock material free of charge, none had round 7075-T6 stock big enough to meet any of the group's concept designs highlighted under "*Design Generation".*

As an alternate solution, Group MA02 then asked them if they carry 7075-T6 flat plates that could then be cut by waterjet (or CNC mill) using McMaster campus facilities, into a round shape for the transducer body, as its overall diameter does not need a tight tolerance. However, none of these sponsors carry 7075-T6 plate stock large enough for any of the design options.

Fortunately, the preliminary budget in the SoW document had set aside $200 in unforeseen costs that could be reallocated to purchase 7075-T6 stock.

Updated Objective:

All concept WFT body designs found under "*Concept Generation"* do not require round stock larger than 6.5 inches in diameter and one inch in length. Additionally, no potential design requires a plate larger than 10in×10in for mounting purposes.

With this in mind, the group reached out to one of the team's material suppliers, *Golden Triangle Specialty Metal Ltd.,* requesting a quote for both round and plate stock of 7075-T6. This quote can be found in "*Appendix C – Material Stock Quotes*" in *Figure 46* and it shows a cost of $39.58 CAD for 6.5in diameter stock (one inch in length), and $53.40 CAD for 10in×10in plate stock.

As a result, the group has conservatively updated our budget objective to set aside $100 CAD for transducer body and mounting bracket stock materials.

Sampling Rate:

Sampling rate is the number of samples taken per second from a continuous signal [9] (in this case, the strain gauges) to make a discrete or digital signal of the strain experienced by the wheel force transducer. In the case of the McMaster Baja Team, the presumed impact/impulse of a sudden force from, say, a jump, is assumed to be 0.2 seconds. This means that the PCB has a window of 0.2 seconds during a sudden force to acquire and determine the maximum strain experienced. A sampling rate too small results in a low-resolution signal that inaccurately records the peak of the strain signal. Whereas a higher sampling rate is costly to the processor and may require a more expensive and complex PCB design.

Shortly after the submission of the SoW document, Group MA02 set an additional objective to create a data acquisition (DAQ) system that samples at the rate of 1kHz. With an impact length of 0.2 seconds, this would result in 200 data points.

Manufacturability:

As discussed in the SoW document and "*Spending and Budget Report*", the budget set aside for manufacturing is $0. This means the selected design must be able to be manufactured using only manual lathes/mills and 3-axis CNC lathes/mills made available to our group (for free) in the Undergraduate Project Laboratory, MMRI, and Hatch Workshop.

Mounting:

The upcoming 2024 McMaster Baja car will have rims with a diameter of 263.5mm free/useable space that a WFT can occupy as seen in *Figure 11*. The suspension sub-team has outlined their desire for the WFT to be mounted onto the hub, pictured to the right in *Figure 11*. The hub has a concentric four stud pattern along a 144mm diameter that the transducer may be mounted onto.

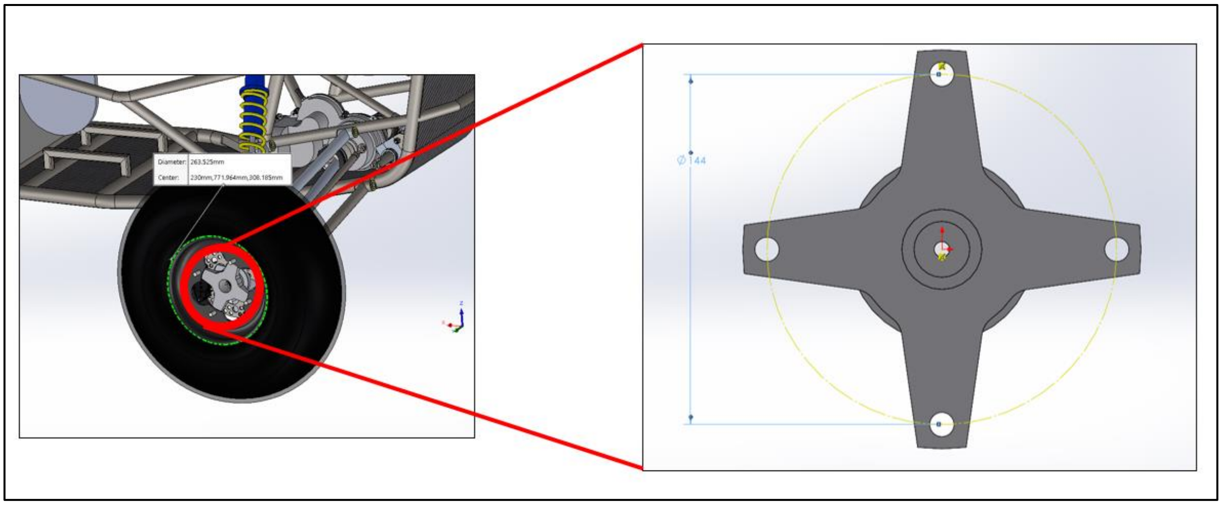

Figure 11: CAD models highlight "free space" within the rim's diameter along with mounting positions on the hub.

Project Objectives, Timeline & Milestones:

The following tables outline the design constraints and objectives overlaid with their projected timeline. These constraints are based on "*Background Research*", "*Problem Analysis*", and on content from the SoW document and end of first term report. A corresponding Gantt chart relating to these timelines can be found in "*Appendix D – Gantt Chart*".

Note, these tables were created during the writing of the SoW document. The Green text highlights the objectives that were met at the time of writing the first term report and were completed on schedule. Additionally, bolded constraints are ones that have been adjusted during the writing of the first term report.

The discussion of whether remaining constraints were met and completed on schedule, can be founder under "*Project Completion Status*" as well as the inclusion of unanticipated milestones.

Table 2: Objectives and deliverables for the transducer body design from the SoW document – green text highlights competition at the time of writing the end of first term report.

Gantt Line #	Milestone	Deliverable	Constraints (if applicable)	Completion Date
		Transducer Body Design		
1.1	Design Generation	Every member must generate at least one concept design for the transducer body using SOLIDWORKS. Designs do not need to be dimensionally correct.	Must be manufacturable with available lab infrastructure Mountable to a four-bolt hub	Oct 13th
1.2	Design Selection	Design selection matrix (with weightings) created and used to select preliminary design.		Oct 20th

1.3	Preliminary Design CAD Complete	Transducer body (and any mounting accessories) CADed and added to McMaster Baja car CAD assembly. Feedback required from project supervisor and Undergraduate Project Lab technicians.	Mountable to a four-bolt hub Fits within Baja rim diameter Overall mass under 6lbs Must be manufacturable with available lab infrastructure ($0 cost) **Material stock costs no more than $100 CAD** All DAQ equipment can be mounted onto it	Nov 3rd
1.4	FEA Test	If preliminary design meets constraints, FEA tests performed to measure FOS and fatigue life with estimated max force and constant stress amplitude.	**Lifespan of 896,000 cycles (Maximum endurance limit of 240MPa)** Minium FOS of 1.25 with 1000lbf radial load and 500lbf lateral load	Nov 6th
1.5	Finalized Design CAD	Design revised based on prior feedback from project supervisor, technicians, and FEA results. Design is manufacturing ready.	Mountable to a four-bolt hub Fits within Baja rim diameter Overall mass under 6lbs Must be manufacturable with available lab infrastructure ($0 cost) **Material stock costs no more than $100 CAD** All DAQ equipment can be mounted onto it **Lifespan of 896,000 cycles (Maximum endurance limit of 240MPa)** Minium FOS of 1.25 with 1000lbf radial load and 500lbf lateral load	Jan 1st 2024
1.6	Test Jig Design	Test jig designed to house the finalized design for applying known forces and moments.	Must be manufacturable with available lab infrastructure ($0 cost) Material stock available from sponsor ($0 cost) Can be assembled with only hand tools All nonmachined components are off the shelf (no lead time) Mountable to Hatch Workshop weld table	Jan 1st 2024

Table 3: Objectives and deliverables for software development from the SoW document – green text highlights competition at the time of writing the end of first term report.

Gantt Line #	Milestone	Deliverable	Constraints	Completion Date
Software Development				
5.1	Microcontroller Software	Code has been developed to record data from each amplifier and rotation sensor.	Must create a 1×6 strain vector denoted as $\overline{\boldsymbol{S}} = \left[S_{F_x}, S_{F_y}, S_{F_z}, S_{M_x}, S_{M_y}, S_{M_z}\right]$ Must write recorded data to a micro-SD card on the PCB board Software can be developed entirely with available numerical tools	Feb 2nd 2024
5.2	Data Convertor	Script developed to convert and save binary data files to readable data onto a micro-SD card	Outputs data in a CSV format Software can be developed entirely with available numerical tools	Feb 9th 2024
5.3	Revised / Finalized software	Software and data viewer has been finalized after testing with the test rig and on the Baja car itself.	Integration with McMaster Baja data viewer	March 15th 2024

Table 4: Objectives and deliverables for hardware development from the SoW document – green text highlights competition at the time of writing the end of first term report.

Gantt Line #	Milestone	Deliverable	Constraints	Completion Date
Hardware Development				
3.1	Strain Gauge Layout	Number of strain gauges, orientation, and relative placement on transducer body decided.	Must fit on transducer design selected. Must be able to provide enough data to create 1x6 strain vector denoted as $\overline{\boldsymbol{S}} = \left[S_{F_x}, S_{F_y}, S_{F_z}, S_{M_x}, S_{M_y}, S_{M_z}\right]$	Nov 3rd
3.2	PCB Design Completed	PCB design completed with assistance from undergraduate project lab technician. All required information/files completed and ready to be	Created entirely with available software (i.e., Altium) detailed above Can be produced by PCBWay ($0 cost due to sponsorship) Designed in conjunction with number of strain gauges selected	Dec 1st

		handed off to PCBWay for production.	Compatible SD card slot for data acquisition Must sample all strain gauges at 1kHz	
3.3	DAQ Housing Designed	Housing designed that can contain the PCB and mount to the transducer.	Can be designed and manufactured entirely with available resources listed above All housing components can be 3D printed Housing can fit and be mounted onto the transducer	Dec 29th
3.4	DAQ System Assembled and Mounted	All required soldering is completed, strain gauges are mounted, PCB is placed in housing and mounted	Can be assembled entirely with available resources listed above	Feb 9th 2024

Table 5: Objectives and deliverables for manufacturing from the SoW document – green text highlights competition at the time of writing the end of first term report.

Gantt Line #	Milestone	Deliverable	Constraints (if applicable)	Completion Date
Inhouse Machining and Manufacturing				
4.1	Transducer Body	Unibody transducer body fully machined and ready for assembly with other components.	Must be manufacturable with available lab infrastructure	Jan 12th 2024
4.2	Transducer Mounting Bracket	Bracket (if required) fully machined and ready for assembly with other components.	Must be manufacturable with available lab infrastructure	Jan 12th 2024
4.3	Test Jig Frame Manufactured	All required blocks are fully machined and ready for assembly with off the shelf components.	Must be manufacturable with available lab infrastructure	Jan 26th 2024
4.4	DAQ Housing 3D Printed	DAQ housing body has been 3D printed and ready for assembly and mounting	Must be manufacturable with available lab infrastructure	Jan 26th 2024

Table 6: Objectives and deliverables for material procurement from the SoW document – green text highlights competition at the time of writing the end of first term report.

Gantt Line #	Milestone	Deliverable	Constraints (if applicable)	Completion Date
Material Procurement				

2.1	Strain Gauges	All strain gauges (quantity TBD) have been sourced, ordered, and received.	Strain gauges and shipping within $50 CAD budget	Ordered by Nov 1
			Lead time allows for arrival by or before completion date	Delivered by Jan 12th
2.2	PCB Ordered and Received	PCBWay provided with all technical documentation, PCB shipped, and received.	Can be produced by PCBWay ($0 cost due to sponsorship)	Order by Dec 1st
			Lead time allows for arrival by or before completion date	Delivered by Jan 12th
2.3	Transducer Stock	Locate local sponsor willing to supply off the shelf stock for the transducer body.	**Material stock costs no more than $100 CAD**	Nov 24th
			Local and off the shelf (can be picked up same day)	
			Stock must be the same as indicated material choice for transducer body	
2.4	Test Jig Stock	Locate local sponsor willing to supply off the shelf stock for the test Jig blocks.	Supplier is sponsor ($0 cost)	Jan 1st 2024
			Local and off the shelf (can be picked up same day)	
			Stock must be the same as indicated material choice for test Jig	
2.5	Test Jig off the shelf components	Locate one or several local suppliers of pulleys, dowel rods, and cables.	Remain within $50 CAD budget	Jan 1st 2024
			Local and off the shelf (can be picked up same day)	

Table 7: Objectives and deliverables for testing and validation from the SoW document – green text highlights competition at the time of writing the end of first term report.

Gantt Line #	Milestone	Deliverable	Constraints (if applicable)	Completion Date
		Testing and Validation		
6.1	Test Jig Assembled	Test Jig is assembled with validation that the transducer fits properly within it.	Can be assembled with only hand tools and resources detailed above	Feb 2nd 2024
6.2	Transducer Tested on Jig	Known loads applied to Transducer for each of the three forces and three moments. Known loads are compared to recorded forces.		Feb 9th 2024
6.3	Transducer Calibrated on Jig	Compliance matrix values finalized so that outputted force readouts	All three force axis calibration curves produce $r \geq 0.9$	March 15th 2024
			All three moment axis calibration curves produce $r \geq 0.9$	

		equate to known forces inputted		
6.4	Transducer Tested on Baja Car	Transducer is mounted onto the Baja car and taken to the test track to collect data.	Test plan/validation TBD	March 22nd 2024
			Transducer can withstand four hours of testing	

Concept Generation:

The following section is an introduction to each of group MA02's three design concepts (one created by each member) for the WFT body. Please see "*Design Concept Selection*" for the evaluation of each design against the design criteria and objectives discussed in depth under "*Selection Criteria*".

Design Concept 1 – Aluminum Strain Plate with Hub Adaptor:

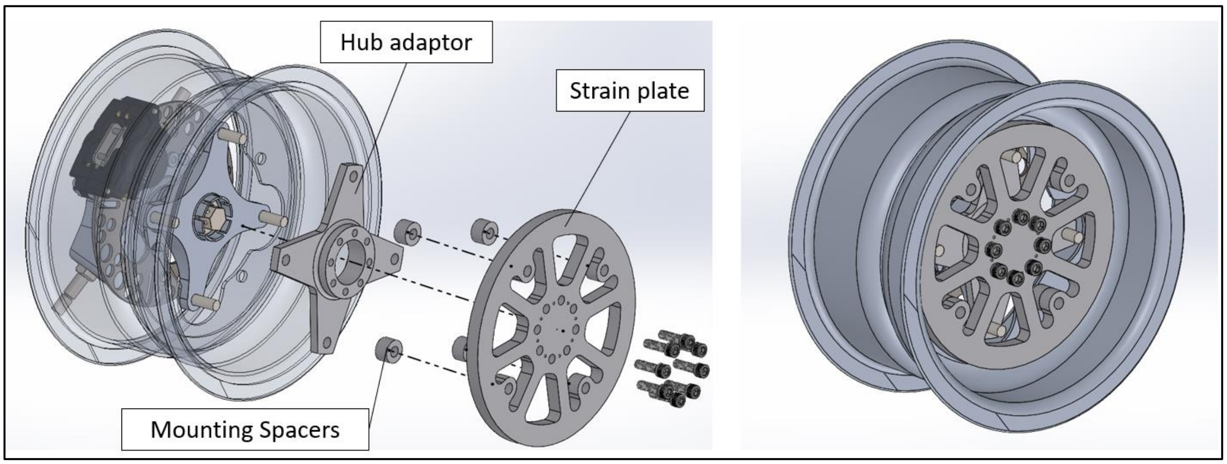

Figure 12: CAD model of a WFT assembly (comprised of a hub adaptor, strain plate, and mounting spacers) assembled onto the McMaster Baja Team's 2024 car's rim.

Figure 12 depicts design concept 1, a WFT body assembly that is composed of a strain plate, hub adaptor, and mounting spacers, all of which are made of 7075-T6 aluminum. In this design, the strain plate (which holds strain gauges) is mounted to both the hub via the hub adaptor, as well as the rim of the vehicle by mounting spacers. Force is transmitted to the strain plate from both the rim and hub through connecting fasteners, causing the strain plate to elastically deform.

This elastic deformation is measured by a total of 32 strain gauges placed along each of the eight spokes of the strain plate (not imaged). This strain gauge layout (and subsequent DAQ process) closely follows *Dr. Feng's* publicly accessible, well documented, and cost-effective method of creating a WFT [3]. A thorough assessment of design concept 1 against the established design criteria (including FOS, fatigue life, cost, ETC.) can be found under "*Selection Criteria*".

Note that the hub design (and rim choice) is the design work of the McMaster Baja Team for their upcoming 2024 season car. This design concept mounts to that car design without requiring any subsequent design changes to the McMaster Baja Team's 2024 car. Many established manufacturers and suppliers of WFTs (such as Michigan Scientific, Kistler, and MTS) exclusively sell models that mount to a car's rim and/or hub, making this design in line with industry standard.

Design Concept 2 – Modified Hub (Integrated Wheel Force Transducer):

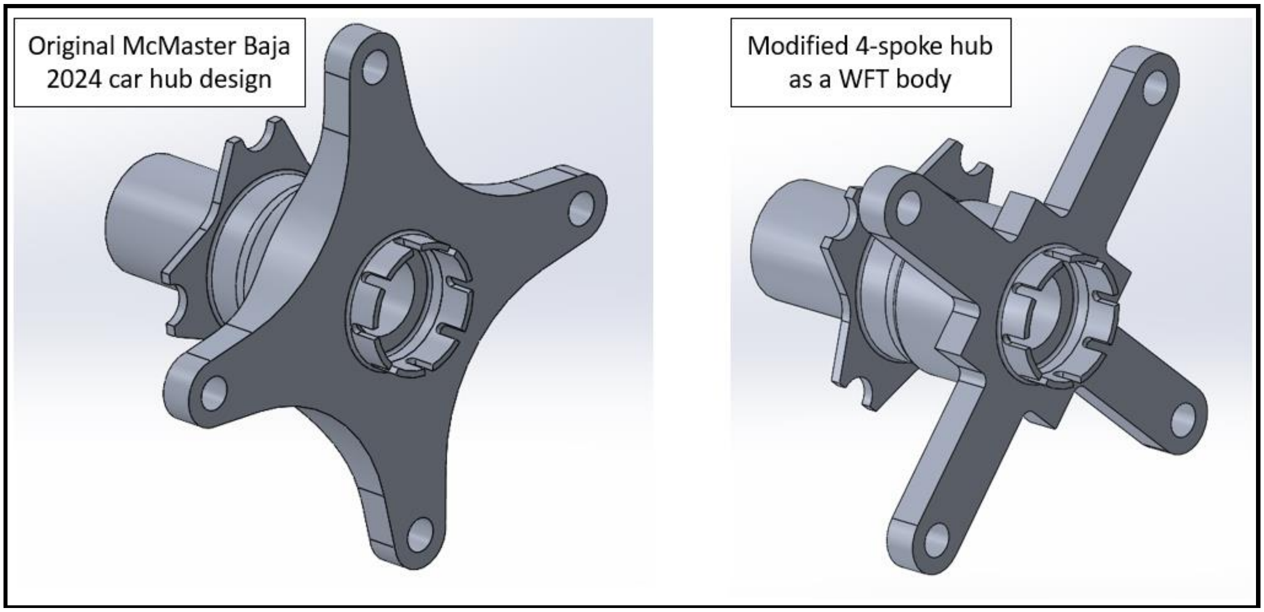

Figure 13: CAD model of a proposed design which investigates reshaping the McMaster Baja Team's hub (on the left) into four rectangular spokes to which strain gauges would be mounted in order to measure strain of the hub (on the right).

Design concept 2 (*Figure 13* pictured above) diverges from the previously mentioned industry standard of WFTs being mounted onto an existing hub and/or rim. Instead, this design concept modifies the design of the McMaster Baja Team's 7075-T6 aluminum hub.

Here, the hub's arms are redesigned into four spokes resembling rectangular prisms, where all surfaces of the spokes are perpendicular to one another. Strain gauges would be installed along each of the spokes of the newly designed hub and would directly measure the elastic deformation experienced by the working hub.

In addition to this design departing from the industry standard of not being mountable (rather becoming a near-permanent installation), this design would be unable to utilize the DAQ system designs of *Dr. Feng* [3]. As discussed later under "*Selection Criteria*", even though there are some publications around the design of a four spoke WFT, Group MA02 has chosen to focus on and use *Dr. Feng's* paper as the basis of this capstone project.

Design Concept 3 – Titanium Alloy Strain Plate with Hall Effect PCBs:

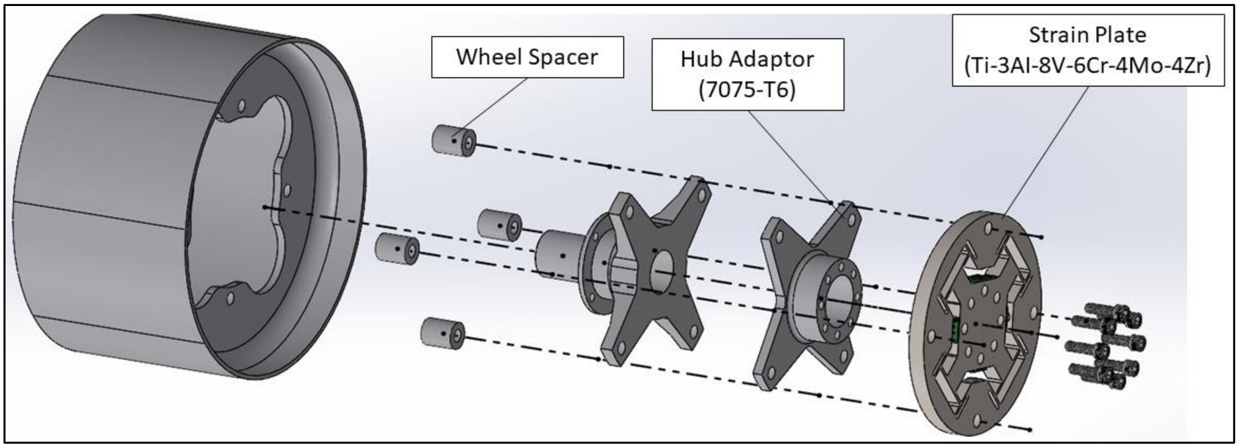

Figure 14: CAD model of a WFT assembly (similar mounting to design concept 1 that employs the Hall effect to measure deformation of the strain plate.

Design concept 3 (shown in *Figure 14*) returns to the industry standard of a strain plate being hub (and/or rim) mounted. This design follows a mounting system very similar to design concept 1, where the strain plate is mounted to both the hub (via hub adaptor) and the rim with the use of wheel spacers. However, this design differs from design concept 1 in two major ways; first, the use of the Hall effect to measure deformation; and second, a titanium alloy (Ti-3Al-8V-6Cr-4Mo-4Zr) strain plate.

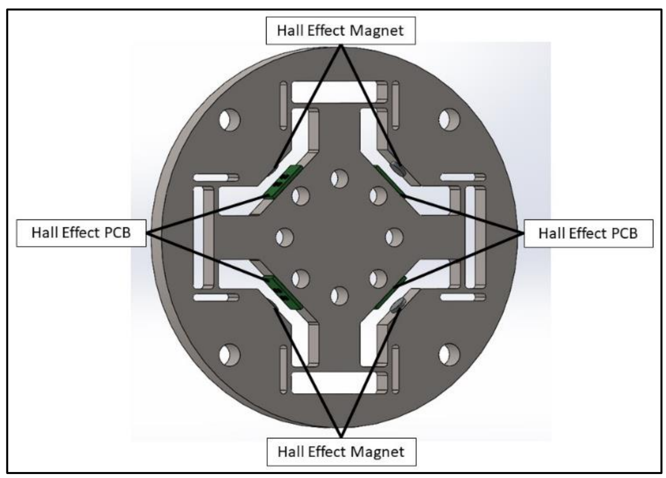

Figure 15: CAD model showing how design concept 3 uses four PCBs and four magnets that employ the Hall effect to measure the deformation of the strain plate.

As seen in *Figure 15,* four Hall effect array PCBs (and four matching magnets) are placed evenly around the strain plate. As the strain plate undergoes elastic deformation, the magnets move with it, changing the presence/magnitude of the magnetic field relative to the sensor. Though many of the cutouts look excessive, this allows the center of the plate to move relative to the magnets and, as a result, is crucial to this design. The overall deformation, measured using the Hall effect, is outputted as a voltage proportional to the displacement. It should be noted that this DAQ concept largely deviates from the work of *Dr. Feng* [3] and, as a result, would require the creation of a novel numerical method system that would convert the displacement (outputted voltages) into force readings.

Additionally, this design concept features a titanium alloy (Ti-3Al-8V-6Cr-4Mo-4Zr) strain plate. Because titanium has the highest strength-to-density ratio of any metallic element [10], this material was selected in hopes of increasing the factor of safety (FOS) and fatigue life of this design while minimizing its mass.

Note that the hub design (and rim choice) is the design work of the McMaster Baja team for their upcoming 2024 season car. This design concept mounts to that car design without requiring any subsequent design changes to the McMaster Baja Team's 2024 car.

Initial FEA Results:

As discussed later in "*Design Concept Selection*", SOLIDWORKS finite element analysis (FEA) was employed to evaluate the fast fracture FOS as well as the fatigue life of each of the design concepts.

Design Concept 1:

Fast Fracture FOS:

After applying a 1000lbf radial load and 500lbf lateral load to the rim of design concept 1, a minimum fast fracture of 2.26 was observed with all bolt tensions set to 15N · m (see *Figure 16*). As discussed in the SoW document and "*Design Concept Selection*", these inputted force values are standardized among the McMaster Baja Team based on legacy values (see *Table 1)*. Note that for this simulation, the hub shaft was constrained as a fixed entity.

Though the FEA indicates a minimum FOS of 2.26 located around the bolt holes, we believe the true FOS is likely higher. It is a common observation for SOLIDWORKS FEA to show exaggerated FOS values along bolt holes due to their infinitesimally small area along the edge. As a result, this infinitesimally small area creates higher stress readouts and, in turn, lower FOS ratings. Accuracy can be improved by minimizing the mesh size, however the computing power available to this group does not allow for that.

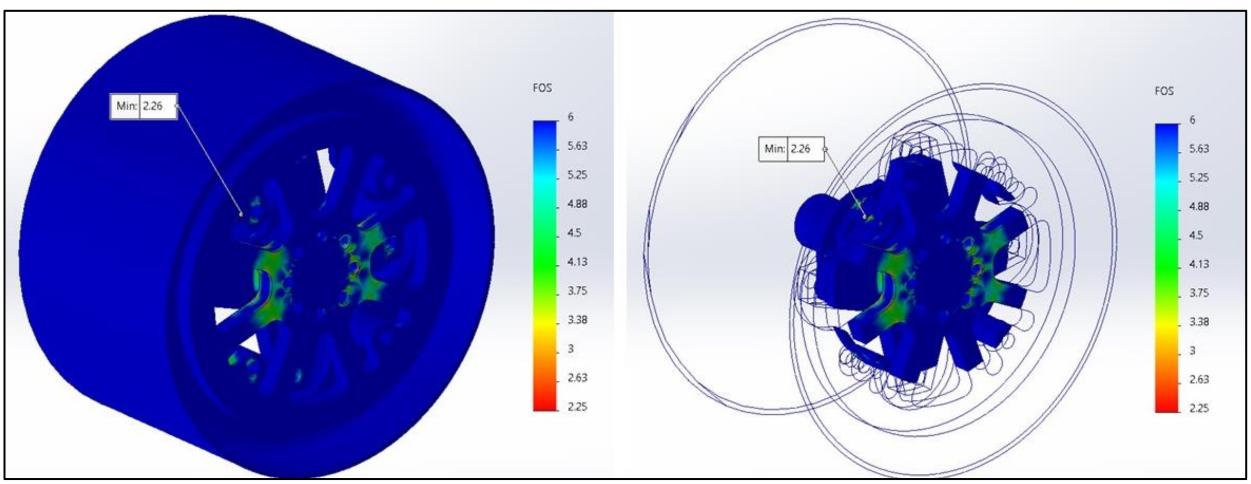

Figure 16: FEA results, indicating a minimum FOS of 2.26 for the 7075-T6 strain plate and hub adaptor design.

Fatigue Life:

Using SOLIDWORKS fatigue analysis software, the lifespan of design concept 1 could be assessed. A completely reversing force of a 100lbf was inputted, in accordance with McMaster Baja Racing standards, for a test composed of 896,000 cycles - the minimum fatigue life of the WFT as outlined under "*Problem Analysis*".

SOLIDWORKS fatigue analysis outputs a damage percentage for a given number of test cycles (FOS of 1). Where a 100-damage percent indicates failure prior (or on) cycle number 896,000. In this case, the maximum damage percent seen for design concept 1 was 11.4%, as seen in *Figure 17*.

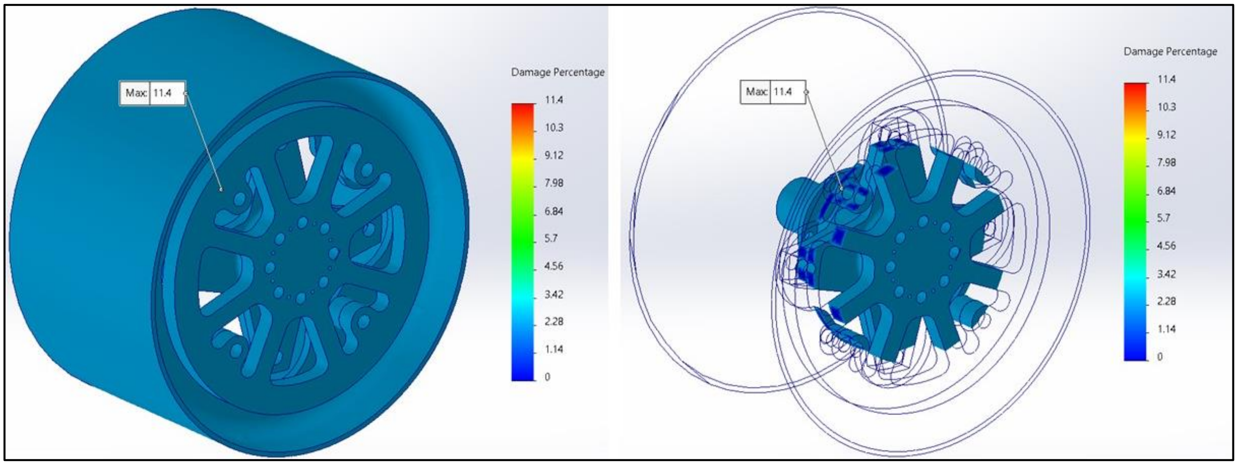

Figure 17: SOLIDWORKS fatigue analysis software result, indicating a maximum damage percent of 11.4% with an FOS of 1.

Design Concept 2:

Fast Fracture FOS:

A 1000lbf radial load and 500lbf lateral load was applied to design concept 2, where an FOS of 1.89 was observed (see *Figure 18*). Note that, unlike the FEA performed for design concept 1, the load was applied using the “remote load function”, simulating the force applied by the hub but without the hub being present. In this case, the four bolt holes were constrained as fixed entities.

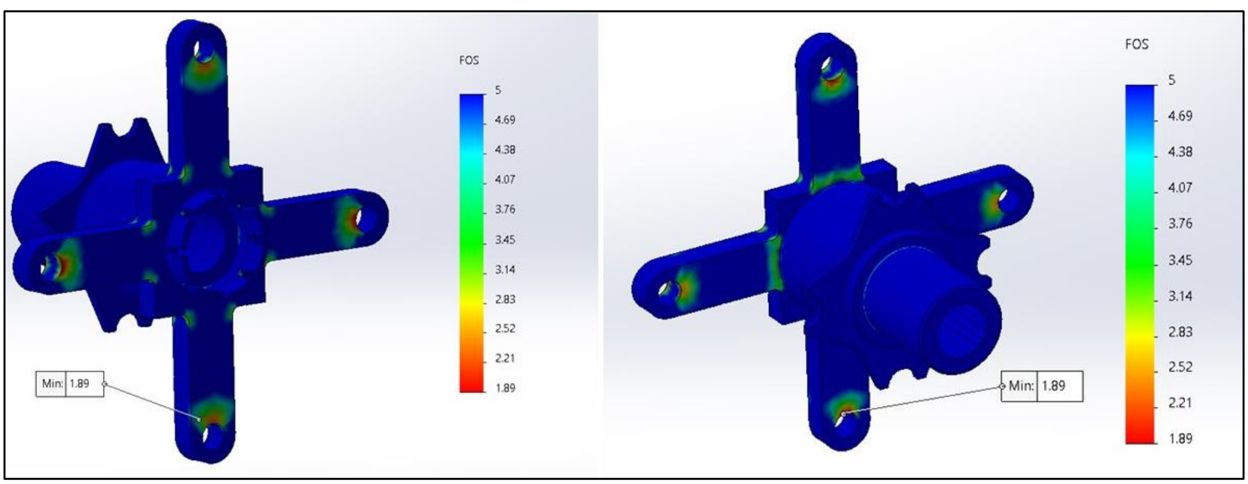

Figure 18: FEA of design concept 2, using the "remote load function" with all four bolt holes fixed in space, which produced a minimum FOS of 1.89.

Fatigue Life:

Since remote loading was used to simulate the force applied to the modified hub, SOLIDWORKS fatigue analysis software could not be used. Instead, the Von Mises stress of the modified hub undergoing cyclic loading with a fully reversible 100lbf load was assessed. According to the S-N curve for 7075-T6 aluminum in *Figure 10*, a stress amplitude of 240MPa will result in failure before the desired cycle life span of 896,000 cycles. Since the majority of the modified hub in *Figure 19* undergoes a stress amplitude of at least 240MPa, it is inferred that this design concept has a cycle life less than 896,000 cycles.

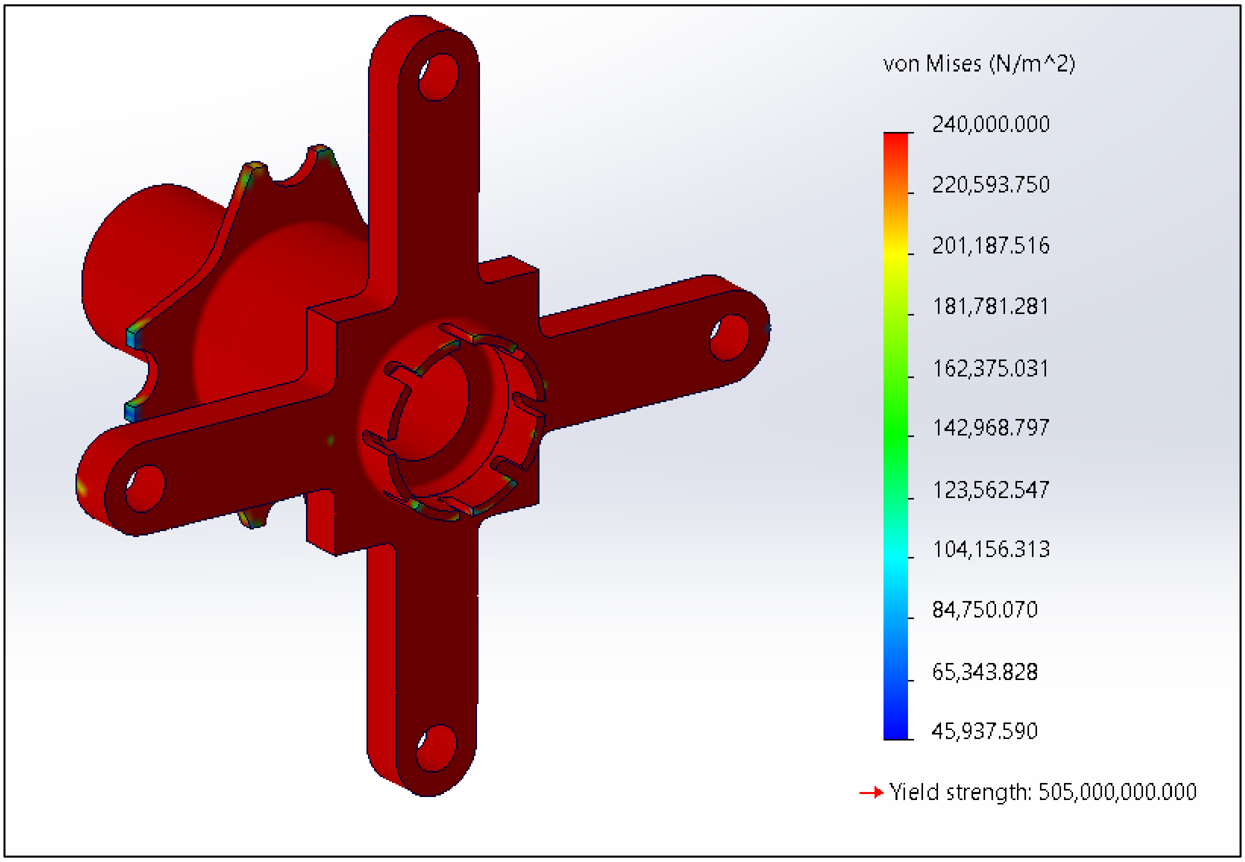

Figure 19: The modified hub design (7075-T6 aluminum), showing a fatigue stress amplitude greater than 240MPa and, as a result, failure prior to reaching 896, 000 cycles.

Design Concept 3:

Fast Fracture FOS:

After applying a 1000lbf radial load and 500lbf lateral load to the rim of design concept 3, a minimum fast fracture of 1.97 was observed with all bolt tensions set to 15N · m (see *Figure 20*). As discussed in the SoW document and "*Design Concept Selection*", these inputted force values are standardized throughout the McMaster Baja Team based on legacy values (see *Table 1)*. Note that the hub shaft was defined in SOLIDWORKS as a fixed entity.

Even though titanium alloy has an ultimate strength of 1220MPa (compared to 572MPa for 7075-T6 aluminum), the FOS for this design is lower than that of design concept 1 [11] [12]. This is likely due to the thin walls and sharp corners created by the material cutouts as the lowest FOS areas are seen there (see *Figure 20)*. This is in line with theory as *Shigley's* highlights both thin walls and sharp corners as the most common causes of high stress concentrations [6]. It should be noted that almost every other portion of the strain plate, aside from the mentioned stress concentrations, exceed an FOS of 5, as seen in *Figure 20*.

Though a simple solution would be to remove, or even minimize these cutouts, this would minimize the motion of the center (PCBs) relative to the outside (magnets), negatively impacting the resolution of data. Regardless, the FOS remains above the design constraint of 1.25 discussed below in “Design Concept Selection”.

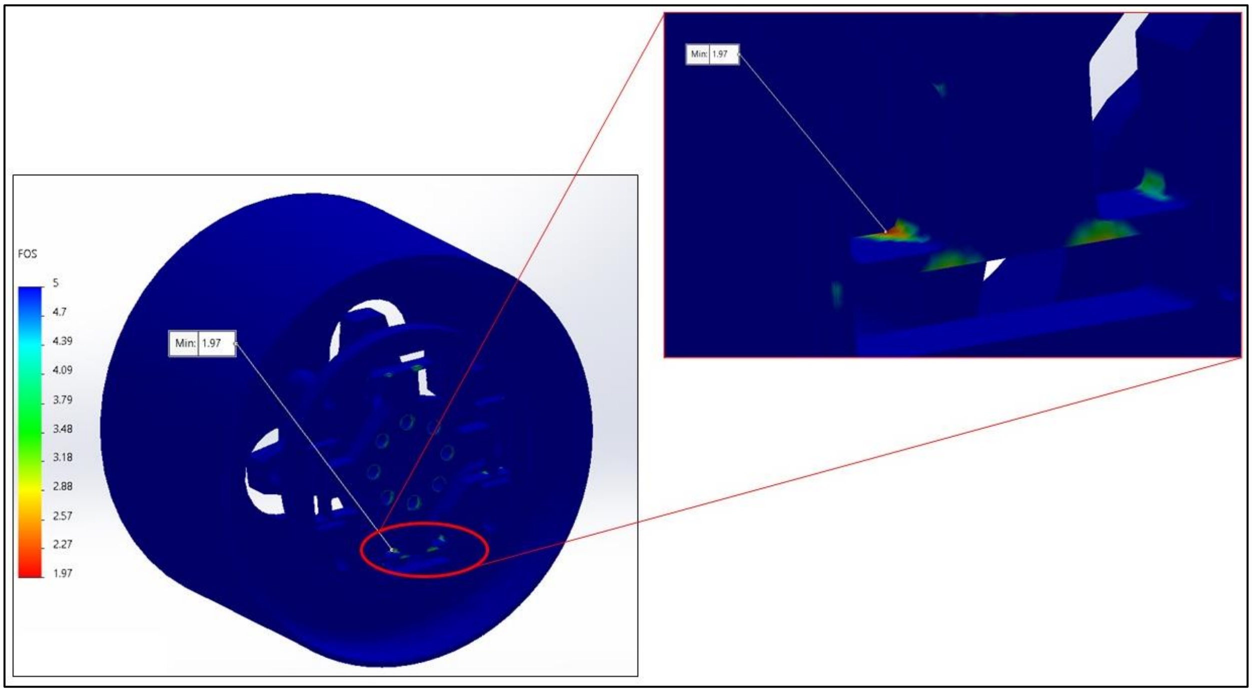

Figure 20: Areas of high stress concentration (top right) are highlighted due to thin walls and sharp corners - lowering the maximum FOS of the strain plate.

Fatigue Life:

Using SOLIDWORKS fatigue analysis software, the lifespan of design concept 3 was assessed. A completely reversing force of a 100lbf was inputted, in accordance with the McMaster Baja Team standards, for a test composed of 896,000 cycles.

Unsurprisingly, SOLIDWORKS indicated that the inputted stress would result in an infinite life (see Figure 21).

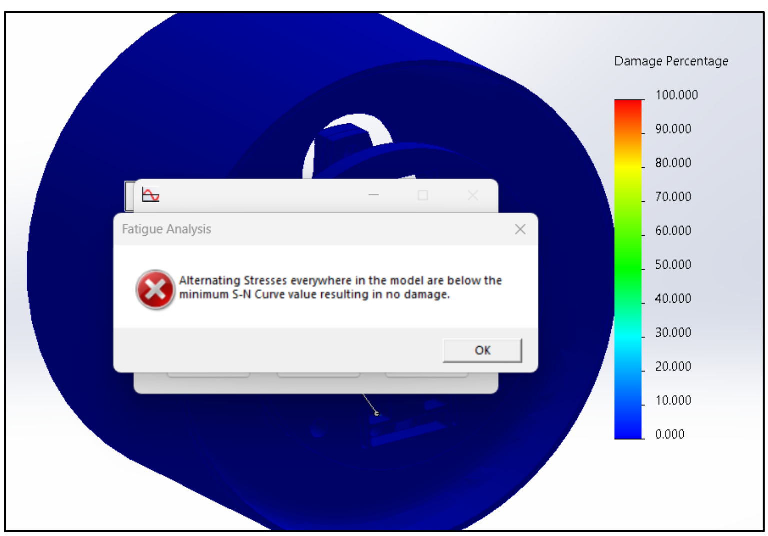

Figure 21: The titanium alloy strain plate is indicated to have an infinite life at the given loading conditions.

Though it may seem counterintuitive that design concept 3 has a larger fatigue life but shorter fast fracture

FOS than concept 1, one must look at the fatigue strength of both materials. As discussed above, under "*Design Concept 3*" the titanium alloy has an ultimate stress nearly double that of the 7075-T6 aluminum but is weakened by the thin walls and sharp corners. However, when comparing fatigue strengths of the two materials, titanium alloy Ti-3Al-8V-6Cr-4Mo-4Zr is rated at 825MPa compared to the 159MPa for 7075-T6 aluminum [11] [12]. Since the fatigue strength of the titanium alloy is more than five times higher than the 7075-T6 aluminum, it is not surprising that the titanium alloy displays an infinite life while simultaneously having a lower fast fracture FOS than the aluminum.

Design Concept Selection:

Method:

Note that this concept selection is focused on the physical WFT body and mounting system design. Detailed hardware and software designs for the DAQ subsystem were not considered in this process as they would be designed and constructed after a WFT body design has been selected. However, heavy preference (and positive grading) was awarded to designs that could incorporate *Feng's* proposed strain gauge based DAQ system [3]. As discussed extensively in the SoW document, and the term one presentation, *Dr. Feng* has created a publicly accessible, cost effective, and "easy-to-understand [DAQ] design procedure - with the aims of [creating] a universal-purpose self-decoupled transducer" [3]. Designs that can incorporate principles from *Dr. Feng's* paper minimize the occurrence of any further project-related issues regarding the DAQ system.

To assess potential designs, a weighted decision matrix was used. Each design was assessed against each design criterion with either the value -1, 0, or 1. A score of -1 indicates that a design does not meet a criterion, 0 indicates that it does, and 1 indicates the best design for said criterion. Though this may be seen as unconventional, the group was able to employ this method as the majority of the specified criteria are quantitative. For the few criteria that are not conclusively quantitative (i.e. manufacturability), a relative grading was used with -1, 0, 1, where a score of -1 is the worst of the three and a score of 1 is best of the three design concepts.

Of course, with it being a weighted matrix, each criterion is also given a relative weight of either 1, 2, or 3. If a criterion has a weight of 1, it is established that if it is not met, it will have little influence on the project and can be worked around. If a criterion has a weight of 2, it indicates that if it not met, several project-related issues will arise as a result. And finally, if a criterion is given a weight of 3, it is a project-critical criterion that jeopardizes the project and its validity if not met.

Selection Criteria:

Criterion 1- Total Mass:

As discussed extensively in the SoW document, end of first term report, and "*Problem Analysis*" it is imperative that the total mass of the WFT is under 6lbs (10% of the car's unsprung mass).

A large unsprung mass, from a WFT, would produce force and load ratings largely above what the Baja car would experience without a WFT attached. These larger readings, deviating from the actual lower value, will counterproductively cause the McMaster Baja Team to overdesign – defeating the purpose of employing a WFT.

Criterion 1 Weighting:

Because the mass of the WFT is directly proportional to the accuracy of force readouts relative to what the car would experience without a WFT, this criterion has been given a **weight of 2**. The reasoning behind this criterion not being project-critical is because the McMaster Baja DAQ sub-team plans on continuing to iterate and improve upon this design every season. As discussed during the first term presentation, the goal of this capstone project is to create a process (and an affordable tool) for the McMaster Baja Team to collect dynamic force data from. As a result, accuracy (though important) is not the primary goal of this project.

Ranking Potential Designs:

All masses listed in the table below have been pulled from SOLIDWORKS and include all mounting accessories (i.e., hub adaptor) but exclude any preliminary DAQ hardware and fasteners. Note that the mass value for design concept 2 was found by calculating the absolute weight difference between the current hub design from the McMaster Baja Team and the modified hub. The absolute value was taken as any change to the unsprung mass would affect the behaviour of the car.

As discussed above in "*Methods*", scores have been assigned on the basis "that -1 indicates that a design does not meet a criterion, 0 indicates that it does, and 1 indicates the best design for said criterion". Because both design 1 and 3 are both under 6lbs, they have received a score of 0 (see *Table 8*). Design 2 has been awarded the highest score (of 1), as it has the lowest change in unsprung mass.

Table 8: Masses of all three design concepts and resulting scoring for the selection process.

	Mass (lbs)	Raw Score
Design 1	2.303	0
Design 2	1.352 – 1.001 = 0.351	1
Design 3	2.95	0

Criterion 2 – Fast Fracture Factor of Safety:

The McMaster Baja Team requires all components to have a minimum fast fracture FOS of 1.25 using Von Mises criteria under the loading conditions of 1000lbf radial load and 500lbf lateral load applied to the rim of the car. Additionally, the team requests that their process is followed for assessing FOS. Each design is to be subjected to said loading in a SOLIDWORKS FEA assembly where an FOS plot can be generated to determine minimum FOS and any areas of significant stress concentrations.

Criterion 2 Weighting:

Because the FOS requirement is greater than 1 and the Von Mises criteria is already conservative, this design criterion has been given a **weight of 2**. Realistically, if all points on a potential design have an FOS greater than one, fast fracture failure is not to be expected and, as a result, is not project critical. Additionally, similarly to the mass objective, the McMaster Baja Team plans on iterating upon the selected WFT design each academic season. Again, the goal of this capstone project is to establish a process (and develop a tool) for the collection of dynamic force data.

Ranking Potential Designs:

All FEAs and resulting fast fracture FOS values can be found under "*FEA Results*". As discussed above, the criterion states that each design must have a minimum fast fracture FOS of 1.25 using Von Mises and legacy loading values (1000lbf radial load and 500lbf lateral load to the rim).

Because design concept 1 had the largest minimum FOS (2.26), it has been awarded the highest score of 1 (see *Table 9*). Both design concepts 2 and 3 have been given a score of 0 as they both exceed the criterion but have a FOS smaller than design 1.

Table 9: Fast fracture FOS values of all three concept designs and resulting scores.

	Min. FOS	Raw Score
Design 1	2.26	1
Design 2	1.89	0
Design 3	1.97	0

Criterion 3 – Fatigue Life:

As discussed extensively under "*Problem Analysis*", the original design objective of creating a WFT with an infinite fatigue life has since been updated. The new criterion states that under a constant cyclic load of 100lbf, the WFT body must have a minimum fatigue life of 896 000 cycles (32 working hours). In the case of 7075-T6 aluminum, the WFT body must have a maximum endurance limit below 240MPa in accordance with *Figure 9* [7].

To assess the endurance limit of a WFT undergoing 100lbf of cyclic loading, FEA will be used to either: one, determine the stress amplitude experienced by a design (see *Figure 19*) and compare this to a materials respective S-N curve or; two, assess the design using SOLIDWORKS FEA fatigue analysis software where a damage percent is assigned for a given number of cycles at a specific loading condition.

Criterion 3 Weighting:

Similar to *criterion 2*, because the fatigue life requirement is still a relatively long lifespan for the purposes of this project, this design criterion has been given a **weight of 2**. If the fatigue life of a selected design comes in marginally below the design objective, this does not put the project in jeopardy and, as a result, is not project critical. Again, similarly to *criteria 1 and 2*, The McMaster Baja Team plans on iterating upon the selected WFT design each season moving forward. It is expected that, at some point, they will receive increased funding or a sponsor that would be willing to provide material with a better strength-to-weight ratio such as titanium.

Ranking Potential Designs:

All FEAs and resulting fatigue damage percents can be found under "*FEA Results*". As discussed above, the criterion states that each design must have a minimum life cycle of 896,000 cycles while undergoing 100lbf of fully reversible loading.

Because concept design 2 experiences a fatigue stress greater than 240MPa, its fatigue life is less than 896,000 cycles according to its S-N curve in *Figure 9*. As a result, design concept 2 has been given the lowest score of -1 for not meeting said criterion (see *Table 10*). Design concept 1 has been given a score of 0 for having a damage percent less than 100%, whereas design concept 3 has been given the highest score of 1 for having the longest fatigue life (infinite).

Table 10: Damage percents during cyclic loading for all three concept designs and their resulting scores.

	Max Damage %	Raw Score
Design 1	11.4	0
Design 2	100	-1
Design 3	0	1

Criterion 4 – Budget:

As addressed under *"Problem Analysis"*, Group MA02 was unable to locate a sponsor for 7075-T6 aluminum stock large enough for two of the design concepts discussed above. As a result, a new design constraint states that stock for the WFT transducer (and any mounting accessories) must be off-the-shelf options that cost less than $100 CAD.

Criterion 4 Weighting:

This design criterion has been designated a **weight of 3**, project critical. Since the project's funding is limited to the $500 CAD from the Department of Mechanical Engineering (pending approval) and the group was unable to find sponsors for WFT stock, the budget of $100 CAD is not flexible. This is because money must also be put aside for the procurement of sensors and off-the-shelf components for the test jig.

Ranking Potential Designs:

As seen under "*Appendix C – Material Stock Quotes", Figure 46* shows a quote from *Golden Triangle* for 7075-T6 aluminum plate and cylindrical stock. As discussed under "*Final Design Selection*", design concept 1 would require 6.5in diameter stock (1in length) and 10in×10in (1/2in thick) plate stock. Referencing the quote in *Figure 46*, this comes to $92.98 CAD - below the specified criterion of $100 CAD.

Because design concept 2 is a variation of the McMaster Baja Team's current hub design, the group would be able to use extra stock that the team has already purchased to machine four hubs and a spare fifth. As a result, design concept 2 would count towards $0 of a stock budget.

Lastly, it was highly difficult to find suppliers who were able to supply off-the-shelf Ti-3Al-8V-6Cr-4Mo-4Zr titanium. However, as seen in *Figure 46*, under "*Appendix C – Material Stock Quotes"*, McMaster-Carr (though not local) can provide off-the-shelf titanium alloy for $216.28 USD. Regardless of the fact that McMaster-Carr's largest stock option is too small for design concept 3, it is indicative of how far out of the $100 CAD budget the titanium alloy of that size (or larger) is.

Overall, because design concept 2 would cost $0 in stock, it has been awarded the highest score of 1 (see *Table 11*). Of course, design concept 1 has been given a score of 0 as it meets the $100 CAD budget but is more expensive than design concept 2. And finally, design concept 3 (a titanium alloy strain plate), has been given the score of -1 for costing several hundred dollars (CAD) above the budget.

Table 11: Project stock costs (based on quotes found in "Appendix A: Wheel Force Transducer Quotes") of each design concept.

	Project Stock Cost	Raw Score
Design 1	$92.98 CAD	0
Design 2	0	1
Design 3	$216.28 USD	-1

Criterion 5 – Compatibility of WFT Body Design with Dr. Feng's DAQ System:

Dr. Feng's paper "Design and optimization of a self-decoupled six-axis wheel force transducer for a heavy truck" is one of few reputable sources that outlines an "easy-to-understand [DAQ] design procedure - with the aims of [creating] a universal-purpose self-decoupled transducer" [3].

Because of this, designs that can use *Dr. Feng's* proposed circuitry (see *Figure 4*) are heavily favoured. Such a transducer body design requires eight evenly spaced elastic columns each capable of housing four strain gauges.

Criterion 5 Weighting:

Because of the distinct lack of design and research papers like *Feng's* [3], the development of such a DAQ system from scratch would be unrealistic to be completed within the two-semester time frame as well as being outside the scope of the mechanical engineering capstone. As a result, this criterion of a design containing eight evenly spaced elastic columns each capable of housing four strain gauges is given a **weight of 3,** project critical.

Ranking Potential Designs:

As discussed extensively in "*Potential Designs*", design concept 1 is the only design of the three that would be able to implement the open-source work of *Dr. Feng* imaged in *Figure 4* [3]. Both design concepts 2 and 3 would require the creation and design of novel DAQ systems to obtain force data.

Because both design concepts 2 and 3 are not compatible with *Dr. Feng's* DAQ system, they have been awarded a score of -1 for failing to meet this criterion (see *Table 12*). Since concept 1 is the only option that meets this criterion and, by default, is the best of the three, it has been awarded a score of 1.

Table 12: Design concepts' compatibility with Dr. Feng's open source DAQ system [3].

	Can it integrate Dr. Feng's DAQ system?	Raw Score
Design 1	Yes	1
Design 2	No	-1
Design 3	No	-1

Criterion 6 – Manufacturability:

As discussed in the *SoW document* and "*Project Objectives, Timeline & Milestones*", the budget set aside for manufacturing is $0. This means the selected design must be able to be manufactured using only manual lathes/mills and 3-axis CNC lathes/mills made available to the group (for free) in the Undergraduate Project Laboratory, MMRI, and Hatch Workspace.

Criterion 6 Weighting:

This criterion has been awarded a **weight of 2**. Since there is the possibility of reaching out to suppliers to perform machining capabilities not available at McMaster (i.e. wire EDM), a potential work-around is possible and, as a result, this is not project-critical.

Ranking Potential Designs:

Design concept 2 is the only WFT body design that cannot be manufactured in full at the undergraduate project lab or MMRI. This is because it requires wire EDM work to create its matching spline for the CV axle. However, it should be noted that the rest of the machining work can be done with a 3-axis CNC mill. Because of this, it has been given the lowest score of -1 for not being able to meet the criteria (see *Table 13*).

Note that design concept 1 and 3 can be completed through the use of a 3-axis CNC mill and manual lathe. Though they include very similar geometric features in both their strain plate and hub adapter design, design concept 1 is easier to manufacture. This is due to design concept 3's strain plate being made of titanium alloy. To machine said strain plate, more time would be required to remove titanium alloy in the machining process. Additionally, speciality tooling would be required that may not be available at the MMRI or undergraduate project laboratory. Because concept 3 can be machined (in theory) with resources already available, it has been given a score of 0, whereas concept 1 (much easier to manufacture) has been given the highest score of 1.

Table 13: Design concepts' scores based off manufacturability.

	Raw Score
Design 1	1
Design 2	-1
Design 3	0

Criterion 7 – Ease of Assembly:

Ease of assembly is one of the few non-quantitative criteria that are a part of this report, but, as the WFT is something that will frequently be put on and taken off the Baja car between tests and competitions, it must be addressed. The scoring for this section will be relative to each of the design concepts, with one concept being the easiest to assemble and place onto the Baja car, and another being the most difficult. All three members of group MA02, having worked on the Baja car over the past five years, can accurately assess how long an install would take, if speciality tools would be required, and if any bench-top equipment (i.e. arbour press) would be needed.

Criterion 7 Weighting:

This criterion has been given a **weight of 1**. Though an easier install and assembly reduces the chances of damaging or breaking the instrumentation of the wheel force transducer, it can be assumed that the people doing said install will have the adequate prerequisite skills. Additionally, the importance of this criterion does not compare in value to others in this report such budget, FOS, or mass.

Ranking Potential Designs:

It must be noted that the McMaster Baja Team will need to frequently install and uninstall the WFT between testing, practice runs, and competition. When assessing design concept 2, it is by far the hardest to frequently install and uninstall as the entire suspension subsystem would need to be disassembled. Hence why the industry standard is a mountable WFT onto a car's rim and/or hub. Because of this, design concept 2 has been given the lowest relative score of -1 (See *Table 14*).

When assessing design concept 1 and design concept 3, their mounting systems seem nearly identical - both use a hub adaptor and set of spacers. However, as seen in *Figure 14*, the strain plate of design concept 3 obscured access to the wheel nuts. Because of this, design concept 3 would require custom tools to reach the wheel nuts and, as a result, would be more difficult to assemble than design concept 1. Therefore, design concept 3 has been given a relative score of 0, where design concept 1 has been given the highest score of 1, as all wheel nuts remain accessible, as seen in *Figure 15*.

Table 14: Relative rankings of ease of assembly and mounting to the Baja car for each design concept.

	Raw Score
Design 1	1
Design 2	-1
Design 3	0

Completed Decision Matrix:

The completed decision matrix (see *Table 15* below*)* has directed Group MA02 to pursing design concept 1, Aluminum Strain Plate with Hub Adaptor.

Table 15: Completed decision matrix (including weightings), indicating design concept 1 as the best overall design.

	Weight	Design Concept 1		Design Concept 2		Design Concept 3	
		Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Total Mass	2	0	0	1	2	0	0
FOS	2	1	2	0	0	0	0
Fatigue Life	2	0	0	-1	-2	1	2
Cost/Budget	3	0	0	1	3	-1	-3
Compatibility with Dr. Feng	3	1	3	-1	-3	-1	-3
Manufacturability	2	1	2	-1	-2	0	0
Ease of Assembly	1	1	1	-1	-1	0	0
Total Score			**8**		**-3**		**-4**

Final Design & Fabrication:

Overview:

As decided by the "*Completed Decision Matrix*", Group MA02 selected design concept 1, an eight-spoke strain plate and hub adaptor as seen in *Figure 22*. After selecting said design, a DAQ system was designed to not only mount on the selected design, but closely follow *Dr. Feng's* publicly available DAQ process [3] as seen in *Figure 4*. The design, procurement, and specifications of group MA02's DAQ system (including the PCB, strain gauges, batteries, etc.) is discussed extensively below in "*PCB Design*" and "*Hardware Selection*".

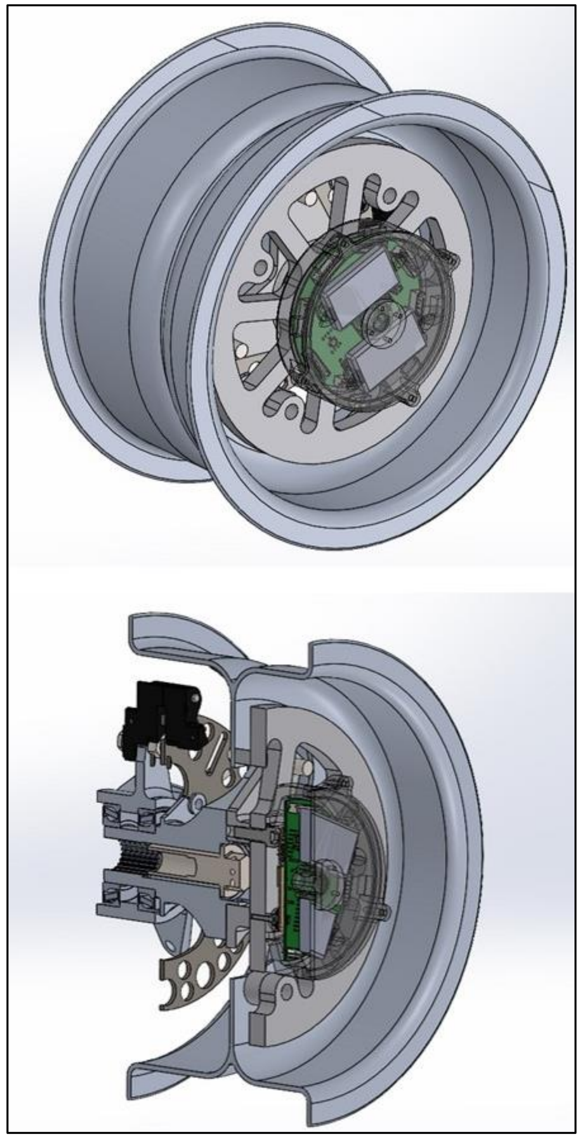

Figure 22: Full and sectioned view of the finalized design mounted onto the rim of the 2024 McMaster Baja car. Note that the DAQ enclosure (and rotary magnet) has been left transparent in both views.

As detailed throughout the remainder of this report, **this design (and the manufactured final product) meets all body design, DAQ hardware, software, and manufacturing objectives** and milestones detailed in *Tables 2, 3, 4, and 5* on (and ahead of) schedule. The timely completion of these objectives as well as all other project objectives (such as calibration) will be discussed thoroughly "*Project Completion Status"* as well as the remainder of this report.

Referring to the exploded view in *Figure 23,* this design transfers the force experienced by the hub and rim into the eight 7075-T6 aluminum elastic columns of the strain plate through the 7075-T6 aluminum hub adaptor, 7075-T6 aluminum wheel spacers, and their corresponding fasteners. As discussed in further detail under "*Hardware Development*", each elastic column houses three strain gauges in reference to *Dr. Feng's* proposed circuitry in *Figure 4* [3]. The PCB collects each sample of strain data and organizes it into a strain vector ($\overline{\boldsymbol{S}} = \left[S_{F_x}, S_{F_y}, S_{F_z}, S_{M_x}, S_{M_y}, S_{M_z}\right]$) using six Wheatstone bridges – one for each primary axis of force/moment. This data is saved onto an SD card (on the PCB) that can then be uploaded (via Wi-Fi) and processed in MATLAB to output force vectors ($\overline{\boldsymbol{F}} = \left[F_x, F_y, F_z, M_x, M_y, M_z\right]$). These force vectors are solved using the equation $\overline{\boldsymbol{S}} = C \cdot \overline{\boldsymbol{F}}$**,** where C is a 6×6 matrix of constants predetermined during tuning and calibration.

As detailed under "*Field Tests & Results*" and "*Project Completion Status*" the final machined (and assembled) product **solves the initial problem statement** of creating an affordable, in-house manufactured WFT that can provide force and moment data (in each of the 6 primary axes) for the McMaster Baja 2024 car.

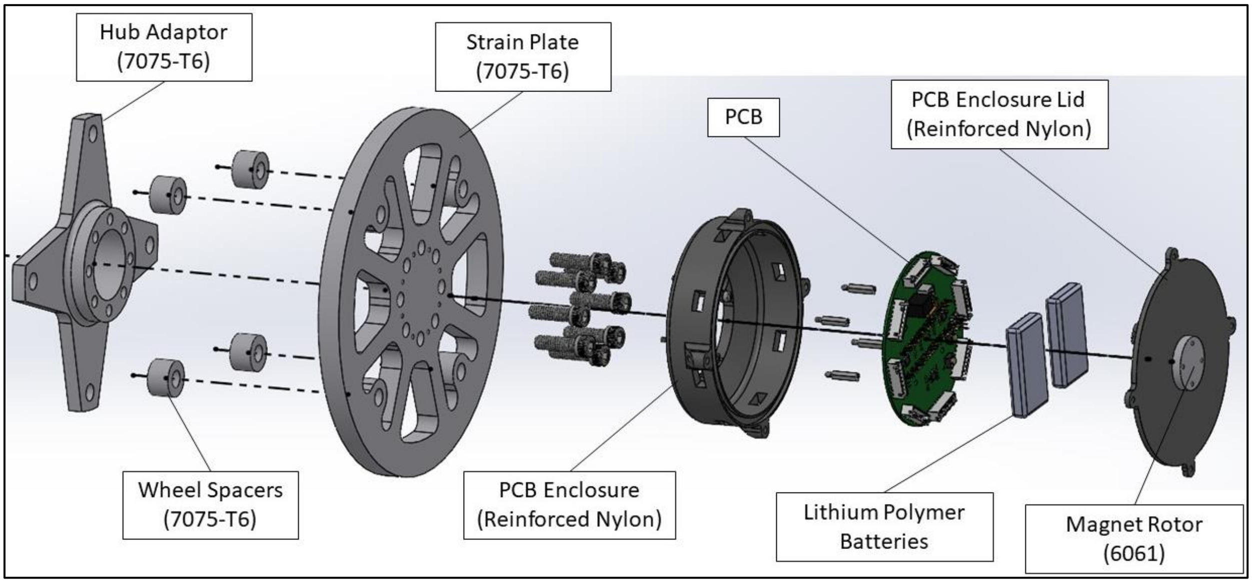

Figure 23: Exploded CAD model of the completed WFT design including the DAQ subsystem.

Wheel Force Transducer Body Design:

Below, *Figure 24* shows only the WFT body assembled onto the McMaster Baja Team's 2024 rim package. A completed drawing package of the assembly can be found under "*Appendix E – WFT Body Drawing Package*". As discussed in detail under "*Assembly*", this assembly transfers the force experienced by the hub and rim into the eight elastic columns of the 7075-T6 strain plate.

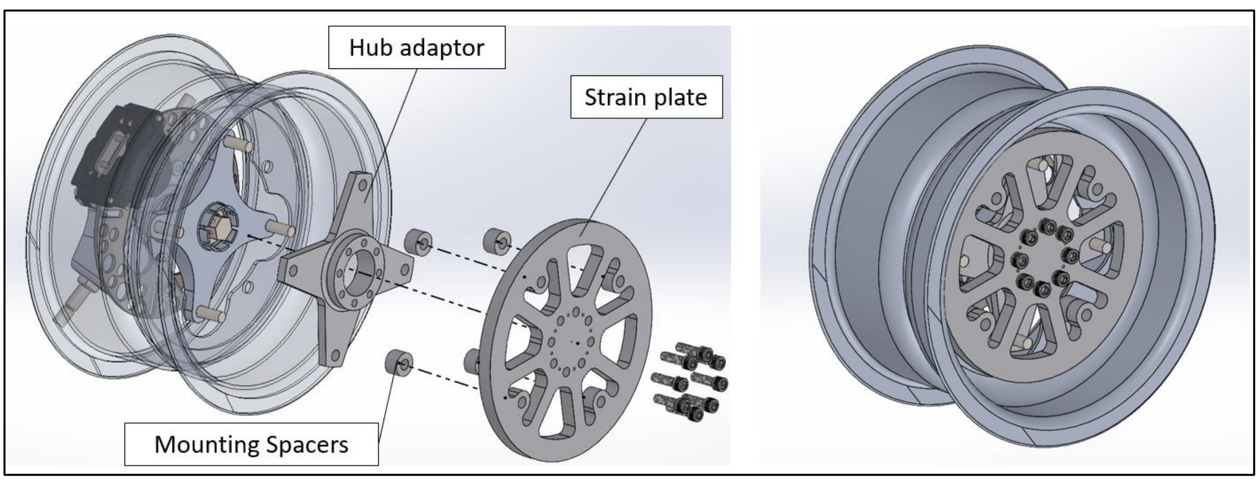

Figure 24: CAD model of a WFT body assembly (consisting of a hub adaptor, strain plate, and mounting spacers) assembled onto the McMaster Baja Team's 2024 car's rim.

The summarized design objectives and constraints from "*Project Objectives, Timeline & Milestones*" pertaining to the WFT body can be found in *Table 16* below. Note that all but one objective/constraints were met. This section discusses how all WFT body objectives and constraints were met.

Table 16: Summary of WFT body design objectives and constraints.

WFT Body Design Objectives and Constraints			
Gantt Line #	Objective / Constraint	Was it Met?	Comments
1.1	Must be manufacturable with available lab infrastructure at $0 cost.	Yes	
1.1	Mountable to McMaster Baja's four stub hub and fit within given rim space.	Yes	
1.3	Overall mass under 6lbs, including DAQ system and fasteners.	Yes	Total mass is disclosed under "*Project Completion Status"*, not this section. Total mass is 3lbs and 2oz.
1.3	Material stock cost no more than $100 CAD.	No	Though the stock budget was exceeded, the surplus purposefully left in the budget covers this cost.
1.3	All DAQ equipment can be mounted onto it.	Yes	
1.4	Lifespan of 896,000 cycles (max endurance limit of 240MPa) for 100lbf fully reversible cyclic load.	Yes	
1.4	Minium FOS of 1.25 with 1000lbf radial load and 500lbf lateral load.	Yes	

Fast Fracture FOS:

Note that the fast fracture FEA of this design was conducted and discussed in depth under "*Initial FEA Results"* and can be seen in *Figure 16*. Recall that legacy values (*Table 1)* of 1000lbf radial load and 500lbf lateral load were applied to the rim of the assembly producing a minimum Von Mises fast fracture FOS of 2.26 as seen in *Figure 25*. Thus, the initial design of the strain plate, hub adaptor, and spacers outperforms the desired minimum FOS of 1.25.

The minimum FOS was located around the bolt holes that connect the strain plate to the hub adaptor. Group MA02 predicts that the minimum FOS is likely higher than shown, as SOLIDWORKS FEA tends to exaggerate FOS values along holes due to their infinitesimally small area along the edge.

Because Von Mises is already conservative and the initial goal of a minimum FOS of 1.25 was surpassed, Group MA02 sees no purpose in further optimizing the WFT body design for a higher fast fracture FOS rating. Instead, the group has elected to focus on the R&D of the DAQ system.

Though a change in material to, say, a titanium alloy or even a steel, would greatly increase the fast fracture FOS, neither material is compatible with the objectives discussed in "*Problem Analysis*". Steel would exceed the project critical constraint of a total mass of 6lbs and stock of titanium alloy of this size for both the plate and adaptor would exceed the cost of the $500 budget allotted by the Mechanical Engineering Department.

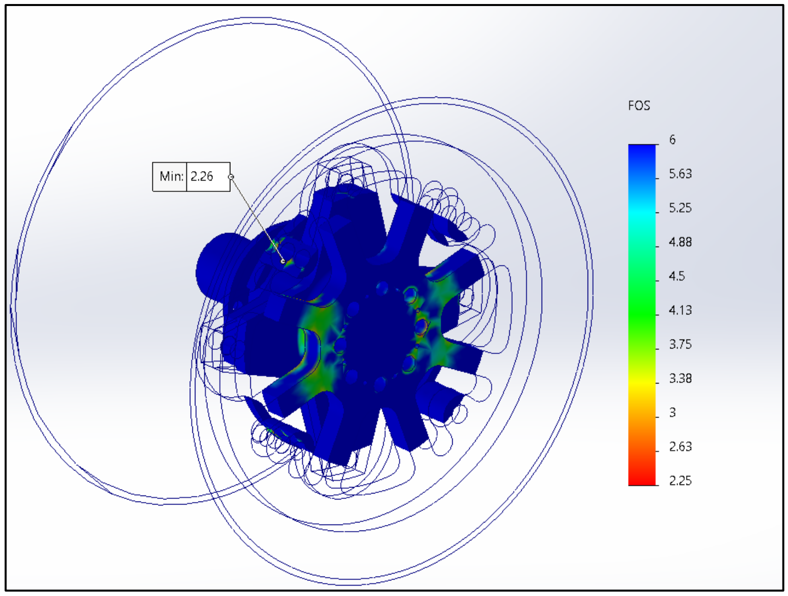

Figure 25: Stress concentrations appear to form at the intersection of the elastic columns and bolt pattern that connects the strain plate to the hub adaptor. However, these concentrations are largely above an FOS of 3.38.

Additionally, as seen in *"Appendix E – WFT Body Drawing Package"*, fillets of a notable radius have been placed where the eight elastic columns intersect the remainder of the strain plate to minimize stress concentrations. Though *Figure 25* shows areas of stress concentration at this location (highlighted in green), the FOS largely remains above 3.38.

Fatigue Life:

Similarly, the fatigue life FEA of this design was conducted and discussed in depth under "*Initial FEA Results"* and can be seen in *Figure 17*. Recall a completely reversing force of a 100lbf was inputted, in accordance with the McMaster Baja Team's standards (see *Table 1)*, for a test composed of 896,000 cycles - the minimum fatigue life of the WFT as outlined under "*Problem Analysis*". SOLIDWORKS fatigue analysis outputs a damage percentage for a given number of test cycles (FOS of 1), where a 100-damage percent indicates failure prior (or on) cycle number 896,000. In this case, the maximum damage percent seen for design concept 1 was 11.4%, as seen in *Figure 17*.

To better assess the success of these results, the number of cycles until failure can be found by referencing the S-N curve for 7075-T6 found in *Figure 10* [8]. To do this, the same test parameters for cyclic loading were inputted and a plot outlining the maximum endurance limit was created. As seen in *Figure 26,* a maximum endurance limit of 224MPa was found along the bolt hole connecting the strain plate to the rim of the car. Cross referencing this with the S-N curve in *Figure 26 (*originally found in *Figure 10),* it can be said that this model is predicted to fail (roughly) on cycle number 1,250,00.

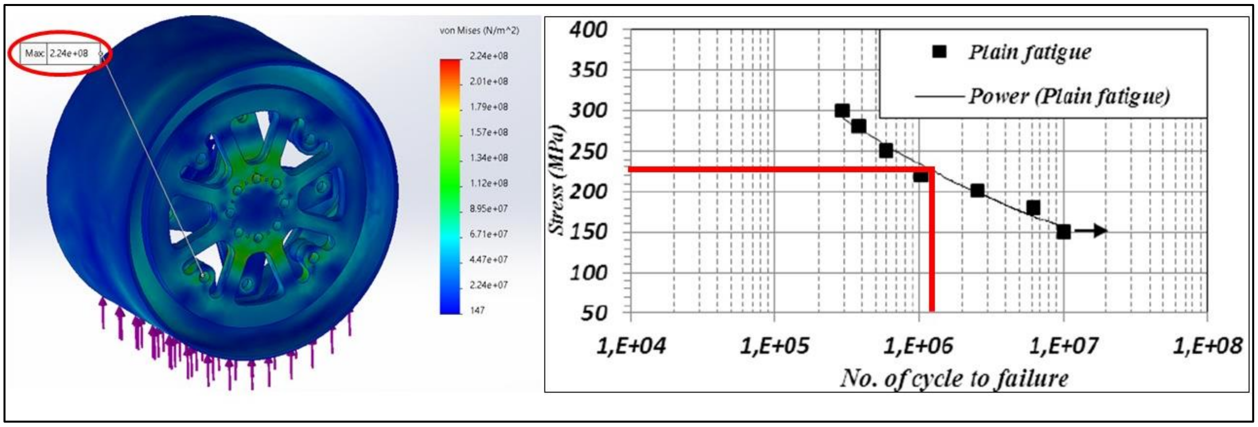

Figure 26: Cyclic loading FEAs indicate a maximum endurance stress of 224MPa for the 7075-T6 design. In correspondence to Zainezhad's S-N curve [8] the WFT body design will fail by cycle number 1,250,000, outperforming the initial design constraint of 896,000 cycles.

Once again, because this simulated value (1,250,00 cycles) outperforms the minimum design constraint of 896,000 cycles (or 32 working hours), Group MA02 has decided that the initial WFT body design does not require further optimization and instead the group can focus on the R&D of the DAQ system.

Manufacturing:

Strain Plate:

As stated previously in "*Problem Analysis*", sponsors for the McMaster Baja Team did not have 7075-T6 cylindrical stock (8in diameter or more) available. Instead Group MA02 was able to source ½in thick plate 7075-T6 stock (10in×10in) from *Golden Triangle Speciality Metals LTD*. As seen in *"Appendix C -Material Stock Quotes",* Group MA02 was able to purchase the stock (off the shelf) for $53.40 CAD. Though cylindrical stock could have been purchased, only ½in in length was needed, below the minimum order length of *Golden Triangle*.

With this plate stock, Group MA02 had the machinists in First Floor JHE Machine Shop waterjet the plate into an 8in diameter (½in thick) cylinder to match the outer diameter found in *"Appendix E – WFT Body Drawing Package".* Though not as accurate at turning cylindrical stock down on a lathe or CNC machine, the outer diameter of 8in is not a critical tolerance/dimension.

Once cut by waterjet into a cylindrical shape, the part was then placed in the CNC mill of the First Floor JHE Machine Shop. Here, all features of the strain plate were completed in a single fixture/clamping setup where different radii cutting tools were used from the same tooling turret. The completed part (seen in *Figure 27*) required no further post processing/machining aside from slight hand sanding in the mounting locations of the strain gauges. As noted in "*Spending & Budget Report",* the total cost (including tax) was $60.34 CAD (stock) as no machining/manfucturing costs were incurred. As highlighted in "*Project Objectives, Timelines, & Milestones*" all manufacturing processes for the WFT were done at no charge

Figure 27: Finished 7075-T6 strain plate after two manufacturing processes; waterjet and CNC milling.

from services available to the group on campus in order to stay within the allotted $500 CAD budget. Note that all G-CODE was created by technicians a service by the First Floor Hatch Machine Shop.

Hub Adaptor:

Similar to the strain plate, sponsors for the McMaster Baja Team did not have 7075-T6 cylindrical stock (6.5in diameter or more) available. Group MA02 once again utilized *Golden Triangle Speciality Metals LTD* by purchasing 6.5in diameter 7075-T6 cylindrical stock in 1.5in length for $122.20 CAD (including taxes). Though this is outside of the $100 CAD budget for WFT material stock ($100 CAD), the surplus in the budget (as discussed in detail under "*Spending & Budget Report")* was able to cover the cost and keep the group on track for staying within the overall $500 budget.

The stock was first turned down into the overall diameter of 164mm on a lathe in the second floor Undergraduate Project Research Lab. Once turned down, the component was cut to rough length on a vertical saw (gravity fed) before being placed back into the lathe to be faced to the final length. The centre hole was also drilled and reamed to the correct diameter using the drill function on the lathe.

As seen in the left most image in *Figure 28,* the component was then dialed in on the rotary table of the first floor Hatch Workshop mill. Here, eight clearance holes were drilled and tapped to 5/16-18 UNC in order to fasten the strain plate to the hub adaptor. Likewise, four locating holes for the hub stubs were drilled and then reamed out.

Once all holes were completed, the remaining material was milled away as seen in the center picture of *Figure 28*. Because each of the four spokes of the hub adaptor are straight (not curved surfaces) the rotary table was used to align each side in the XY coordinates of the mill allowing for cutting motion to occur in a single motion perpendicular to the X axis for each of the eight spoke faces. Once completed, the remaining material of the four spokes was brought down to the appropriate thickness via face milling, creating a protruded surface for the strain plate to mate to as seen in the right most image of *Figure 28*.

Similar to the strain plate, The completed part (seen in *Figure 28*) required no further post processing/machining. As noted in "*Spending & Budget Report",* the total cost (including tax) was $122.20 CAD (stock) as no machining/manfucturing costs were incurred. As highlighted in "*Project Objectives, Timelines, & Milestones*" all manufacturing processes for the WFT were done at no charge from services accessible to the group on campus in order to stay within the allotted $500 CAD budget.

Figure 28: The leftmost image is the turned workpiece on the mill rotary table after all holes have been drilled, tapped, and reamed. The centre image showcases material removal using a rotary table to create the four spokes. The rightmost image shows the completed 7075-T6 hub adaptor.

Spacers:

Unlike the strain plate and hub adapter, cylindrical 7075-T6 stock for the four spacers was made available to Group MA02 at no charge from the McMaster Baja Team. The cylindrical stock, of only 1in diameter and 3in length, is one of the many excess stock items included in the McMaster Baja Team's collective inventory over several years of manufacturing.

The entire stock was placed in the lathe and brought down in its entirety to 0.80in diameter, with the exception of the portion in the chuck. Though a long piece of stock protruding from the chuck introduces vibrations (negatively effecting accuracy) the overall diameter (and finish) of the spacers is not a critical tolerance nor feature. Once the stock was turned down to the appropriate diameter, four spacers were cut with a parting tool slightly above their final length. Each spacer was then placed in the lathe and faced to the appropriate lengths found in *Appendix E – WFT Body Drawing Package"*.

Because all machining occurred on campus in undergraduate workspaces, and the stock was gifted from the McMaster Baja Team, $0 in cost were occurred in the manufacturing of the four spacers.

Assembly:

In order to assemble the WFT onto the car's wheel, the hub adaptor was first fastened to the strain plate via eight 5/16-18 UNC hex head bolts. Once secured, the adaptor and strain plate were fastened to the threaded studs of the hub with four 3/8-16 UNC locknuts. The spacers were then placed behind the strain plate before four 3/8-16 UNC locknuts and hex bolts secured the strain plate to the rim. Though it seems counterintuitive to assemble it in this order, the hub adaptor must be connected to the strain plate first to allow for easy mounting/removal of the DAQ system, as the PCB enclosure (pictured in *Figure 23)* obstructs the view of all eight through holes that connect the strain plate to the adaptor.

PCB Design:

PCB Design Objectives and Constraints			
Gantt Line #	Objective / Constraint	Was it Met?	Comments
	All 6 Wheatstone bridges are connected internally on the PCB	Yes	
	Board must have only 2 layers and be within a 100x100 mm square to reduce production costs	Yes	
	All PCB components must be normally stocking and easy to procure	Yes	
	Any surface mount components must be solderable by hand	Yes	Smallest allowable IC size is TSSOP, and smallest allowable passive is 0603
	Must use a mass storage device for data collection (SD card, USB drive)	Yes	

	Must have the ability to communicate and retrieve files wirelessly	Yes	

Manufacturing:

The McMaster Baja team has a sponsor credit with the company PCBWay, making the cost of production free. Due to the limited credit however, guidelines were followed to reduce the cost of the PCB. This involved limiting the diameter of the PCB to 100mm, and restricting the board to 2 layers. This made routing the bridge connections difficult, as there are 64 incoming connections, some of which need to be connected directly from one side of the board to the other. The use of surface mount components made this routing much easier, as the only through hole components used were the Teensy 4.1, power supply, buttons, and connectors. While this made soldering all the components more difficult, it was a necessary compromise to enable the PCB to fit within the required size.

Hardware Selection:

Many strain gauge options were considered, with different sizes and resistances available. The BF350-3AA strain gauges were selected as they are small and low cost, fitting perfectly within the needs of the project. Adhesive terminals were also used to transition from the small solid core enameled wires from the strain gauges to the larger gauge wires that connect to the PCB. These solder terminals also provide strain relief, preventing the strain gauges from being ripped off the surface when tension is applied to the wires.

Once the strain gauges were all applied, there were some bridges that were out of balance. This was initially fixed by using trimmer potentiometers to add resistance to one side of the Wheatstone bridge, but any vibration or temperature changes would cause the resistance to change, resulting in an unbalanced bridge. The potentiometers were instead replaced with sections of Constantin wire, cut to an exact length. These wires were added to the Wheatstone bridge and glued to the strain plate. The use of Constantin wire also ensured the bridges were still temperature compensated, as the resistance change with temperature changes is minimal.

The AS5600 magnetic encoder was used for rotational position as it had a small package, and had 12 bit accuracy. Other surface mount encoders with more precision were available, but had far more pins to route, and were much more costly. The 12 bit accuracy is also far more than what is required by the design, making it the optimal choice.

The INA2332 instrumentation amplifiers were selected over standard operational amplifiers as they had far less noise at high amplification, and could reach a gain of 1000 which was necessary for the Fx and Fy axes. These ICs also came in 2 amplifier packages, meaning only 3 were needed on the PCB, reducing the amount of routing and soldering required.

Hardware Mounting:

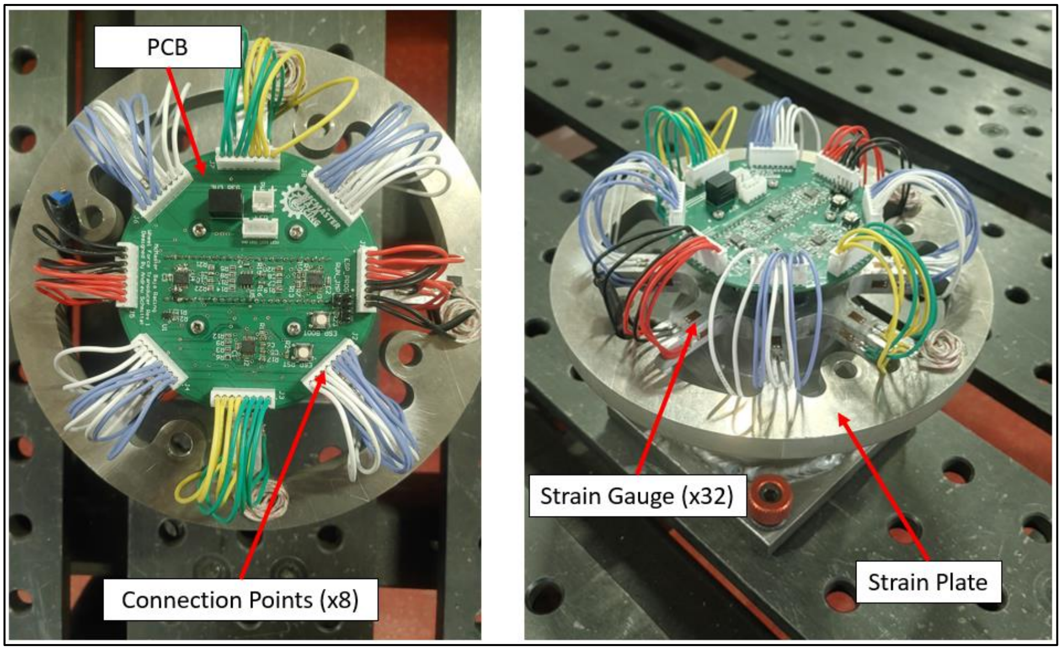

Figure 29: PCB mounted to the strain plate and connected via eight radial connection points.

DAQ Housing Design:

While the structural components of the WFT were made to withstand the expected impacts seen by the Baja vehicle, the PCB, strain gauges, and wires are all exposed to the environment and can be damaged easily in the case of an impact. A housing was designed to both protect the PCB and support the shaft for the encoder magnet.

A plastic strap was also used to connect the magnet rotor to a stationary component on the suspension. This was made using HDPE, which the McMaster team had in excess, so none had to be purchased.

Manufacturing:

Carbon fiber reinforced nylon was used as the material for the DAQ housing, as it could be 3d printed allowing for a more flexible design. The components were printed on a Prusa MK3S along with a filament dryer, which ensured no moisture was present during printing to improve the quality.

Software Development:

All of the code for both the Teensy 4.1 and ESP32 was made in the C++ language using Visual Studio Code with the PlatformIO extension. This made programming the communication code far more robust as a common header file was used for communication constants. In *Figures 30 and 31* the general flow of both programs can be seen, where the ESP32 handles wireless communication and the Teensy 4.1 sends the necessary data while handling the datalogging and SD card functions.

Wireless functionality was a necessity to make the WFT easy to use in the field. Based on the Baja team's previous testing experience, it was clear that a wireless interface was necessary to make logging and labeling files convenient. Files are also date stamped automatically based on the system time of the device connected, so no real time clock or GPS module is required. This timestamp is also used with the team's data viewer to synchronize any videos with the graphs.

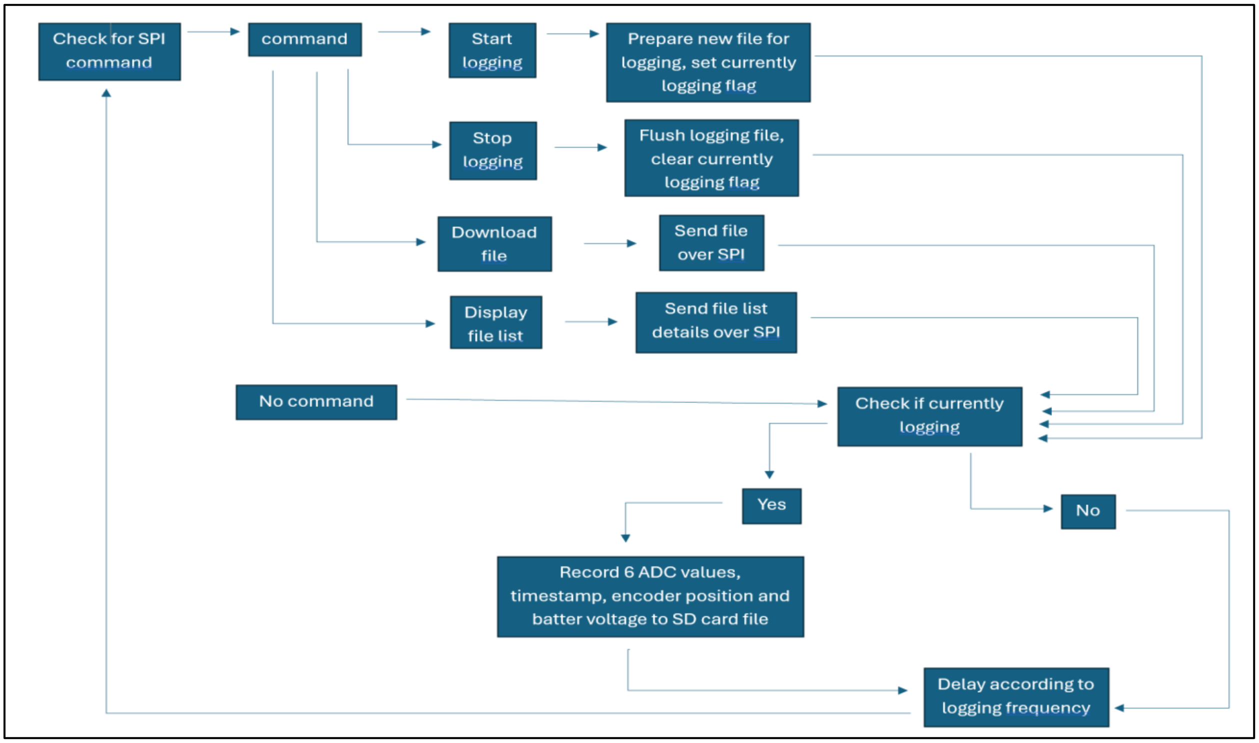

Figure 30: Code flowchart for Teensy 4.1.

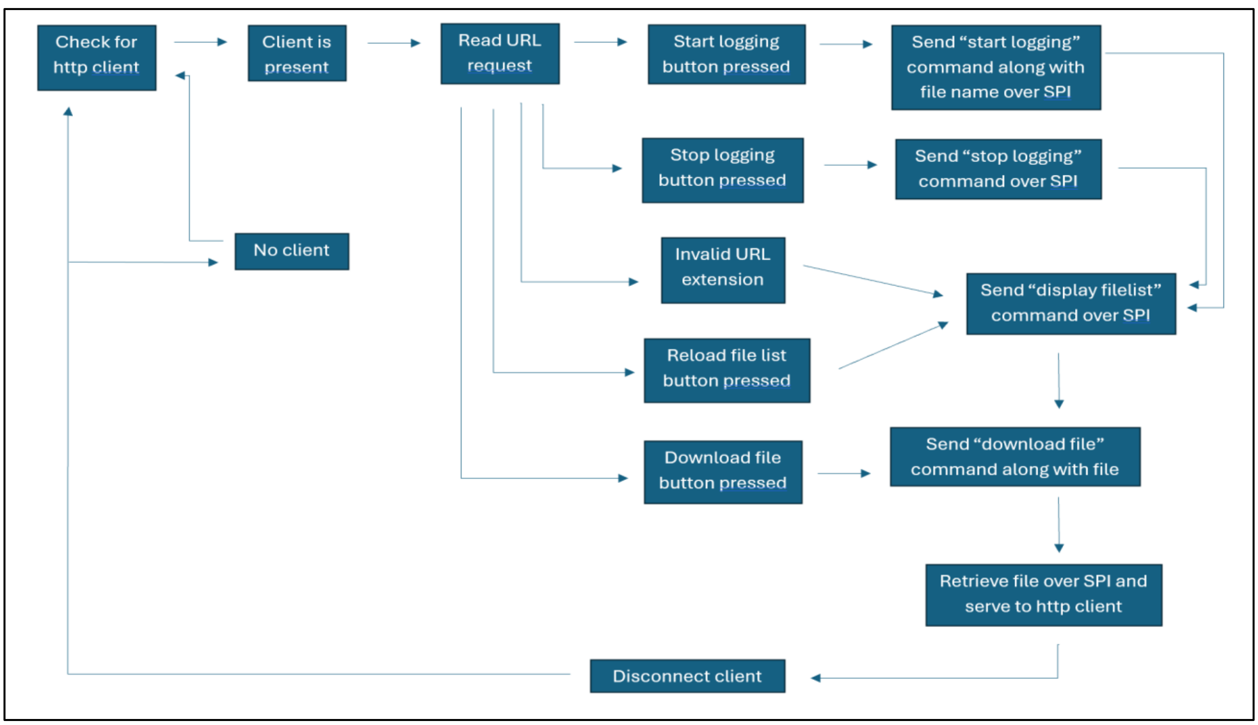

Figure 31: Code flowchart for ESP32.

Calibration:

In parallel to the development and manufacturing of the DAQ hardware and software, Group MA02 successfully completed the design, manufacturing, and assembly of a calibration jig. Such a jig is required to not only tune the DAQ system but to verify the accuracy of its outputted strain vectors and in turn, its calculated force readings. This section details how a calibration jig was designed, manufactured, and utilized (as well as the resulting calibration curves) to verify Group MA02's WFT.

The summarized design objectives and constraints from "*Project Objectives, Timeline & Milestones*" can be found in *Table 17* below. Note that all objectives and constraints were met. The calibration section of this report discusses how all calibration jig design objectives and constraints were met.

Table 17: Summary of all calibration jig objective and constraints being met.

Calibration Jig Objectives and Constraints			
Gantt Line #	Objective / Constraint	Was it Met?	Comments
6.2	Known loads can be applied to the transducer in each of the three forces axes and corresponding moment axes.	Yes	
6.3	All three force axis calibration curves, and all three moment calibration curves, produce a $r \geq 0.9$.	Yes	
1.6	Must be manufacturable with available lab infrastructure at $0 cost	Yes	Manufactured by sponsor *Mancor Industries* instead – at no cost
1.6	Material stock available from sponsor at $0 cost	Yes	
1.6	All nonmachined components are off the shelf (no lead time) and within $150 CAD	Yes	
1.6	Can be assembled with only hand tools	Yes	
1.6	Mountable to Hatch Workshop weld table	Yes	

Calibration Jig Design:

As mentioned previously in "*Problem Analysis", Kebede's* cost effective WFT calibration jig design (seen in *Figure 7)* became of interest to Group MA02 [5]. In this paper, *Kebede* creates a calibration jig that suspends known weight (force) from a WFT. He utilizes a series of pulleys to redirect the force into the desired direction and/or moment.

Group MA02 recognized that they could create known weights (forces) by utilizing construction buckets and spare steel stock from the McMaster Baja Team's shop space. To measure the weight of this steel stock in a bucket, the team's crane scale was used. At this point, Group MA02 had decided on a method of creating known force but would still need to figure out how to apply it to the WFT, as well as redirect it as needed.

Group MA02 first created a mounting post that would fix the WFT and its rim in position (0 degrees of freedom) onto the weld table using available weld table fixture pins (see *Figure 32)*. This design includes two components aside from the WFT and rim: the mounting post, and mounting plate. The mounting plate has five holes, four of which (in the corners) are to fix it to the weld table with fixture pins. From there, a mounting post is turned down on a lathe to include a large body and an integrated locating pin that is not visible in *Figure 32*. The WFT strain plate is bolted to the large body of the mounting post, where the contacting surface of the mounting post and mounting plate are welded together. As discussed under *"Manufacturing"* this was purposefully done in two parts to simplify machining processes and allow one of our sponsors, *Mancor Industries*, to laser cut the mounting plate at no cost.

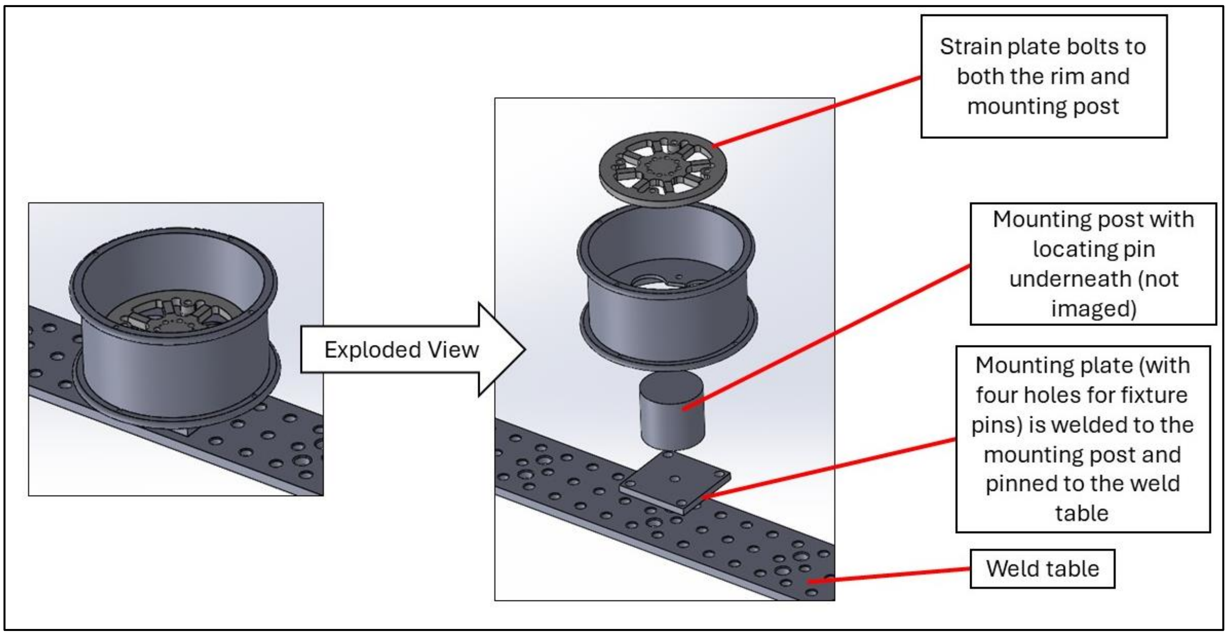

Figure 32: Early design concept of how to fix the WFT and rim to the weld table but allow for quick mounting and removal via fixture pins.

With the WFT and rim mounted to the weld table, deciding on a method to mount the weighted buckets and direct their force was the next step. It was decided that two custom C-clamps would be manufactured and attached to the rim. These C-clamps (see *Figure 33)* include three positional holes to mount the weighted buckets from. The center hole is in line with the WFT strain plate, where the lower and upper holes are spaced at equal distances from this hole. To direct the weighted buckets and their corresponding steel cables, pulley towers that can interface with the weld table are used. As seen in *Figure 33*, four pulley towers and two pulley bases were laser cut at no cost by one of our sponsors (see "*Manufacturing"* below). The pulley towers and bases were then welded together at no cost using the welding equipment available to undergraduate mechanical engineering students. Then welded pulley profiles were 3D printed at no cost from the Undergraduate Project Lab. These pulley wheels where then used to house pressed bearings that were purchased off the shelf for $12.50. *Figure 35* shows the completed calibration jig assembly without the waited buckets. Note that the pulley's location along the weld table can easily be adjusted as it is fixed with fixture pins. Additionally, the pulley height is easily interchangeable by simply moving the pulley to a different rung on the pulley tower.

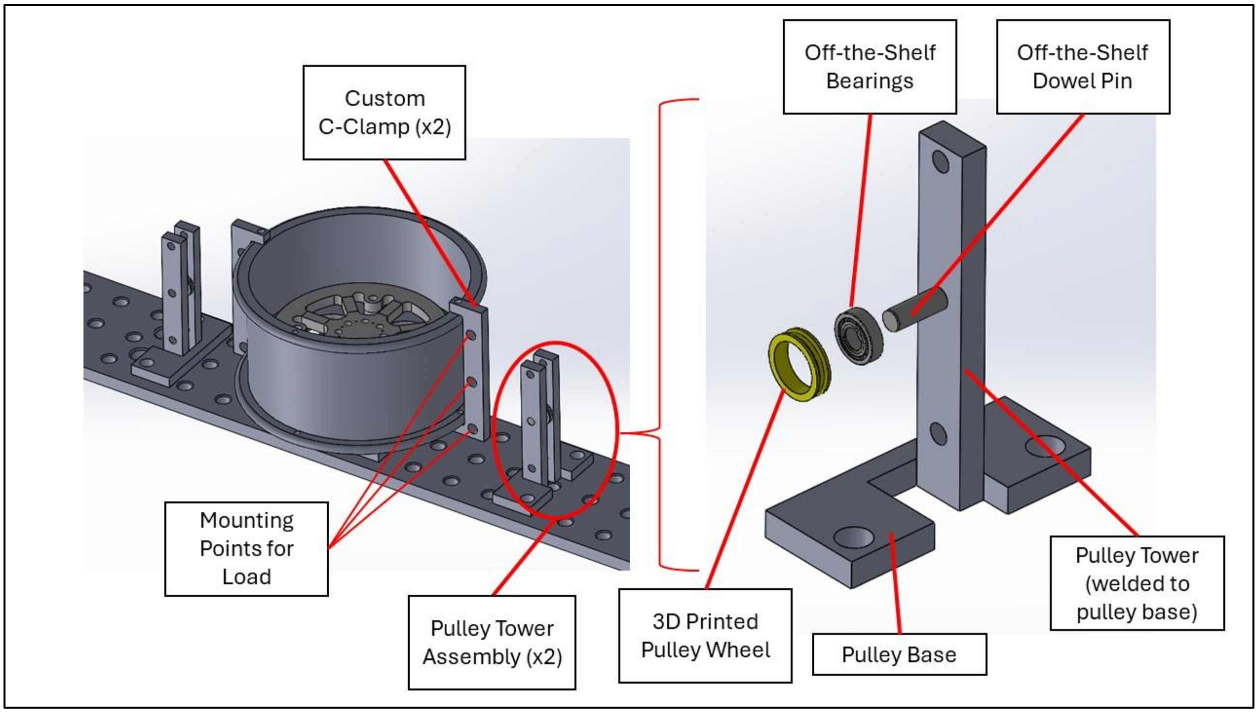

Figure 33: CAD assembly of finalized WFT calibration jig. Pulley position can be changed along the weld table with fixture pins as well as pulley height along pulley tower.

At first glance of *Figure 33,* it can be difficult to understand how all three force axes and all three moment axes can be tested with this single assembly. For one, it is important to note that the position of the pulley relative to the weld table can easily be changed by removed and adding fixture pins to the pulley base. Additionally, the pulley height can be adjusted to guide the weighted buckets to the matching C-clamp loading point. *Figure 34* below showcases how all three force axes and all three moment axes were tested. Note that, for the force denoted as "*F2"* in *Figure 34,* no pulleys were used. Instead, the weight was simply hung from the bottom rung of the C-clamp.

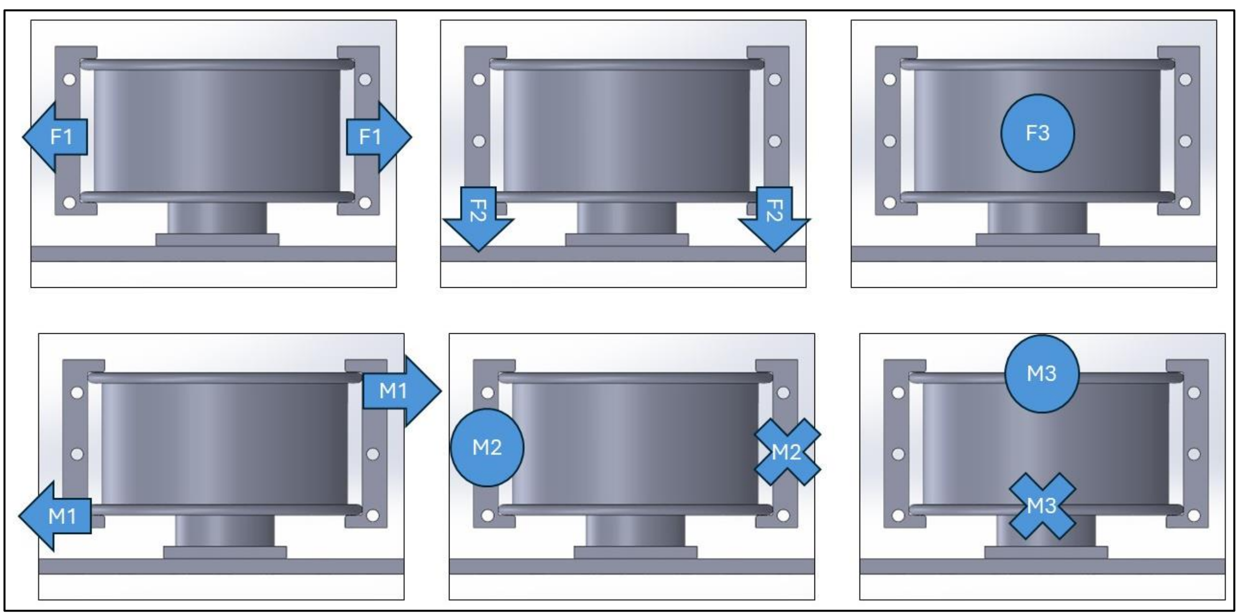

Figure 34: All six force and moment axes can be tested by reconfiguring attachment point and pulley height.

For example, *Figure 33* shows the completed WFT calibration rig with a known applied force in the X-axis (F1). In this configuration, the load transferring steel cables are connected to the center rung of the C-clamp, making the force perfectly in line for the strain plate. To assure that this load is perpendicular to the strain plate, the two pulleys are set to the matching C-clamp height.

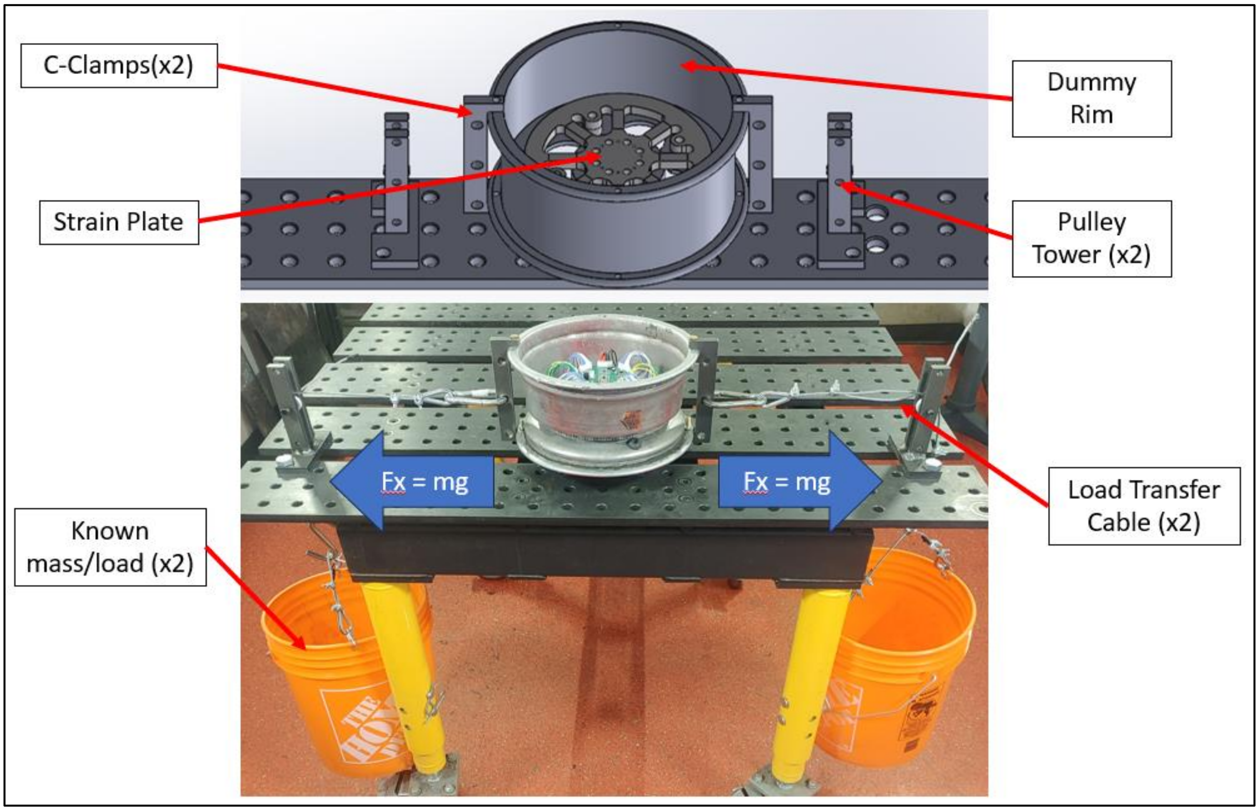

Figure 35: The final assembled calibration jig (bottom) applying a known force in the X-axis. The CAD above has been included for reference.

Calibration Jig Manufacturing:

Note, off-the-shelf components seen in *Figure 33,* are not discussed in this section but are instead highlighted in the "*Spending & Budget Report" section*.

Pulley Base, Pulley Tower, Mounting Plate, & C-Clamps:

At the beginning of the calibration jig design process, Group MA02 reached out to the McMaster Baja Team's sponsor, *Mancor Industries*, in hopes of receiving steel. Group MA02 recognized that all components of the calibration jig would essentially be cantilever arms that the forces would pull against putting them at high risk for fracture - hence the use of steel.

Mancor Industries instead offered to not only provide all required ½in steel plates, but also free use of their 12kW laser cutter powerful enough to cut ½in steel. With time and budget in mind, Group MA02 decided to manufacture as many parts of the calibration jig as possible using *Mancor*'s laser cutter. Not only does this meet the design constraint of spending $0 on stock and manufacturing, but also accelerates the manufacturing timelines when compared to members of Group MA02 manually machining all components.

As a result, the two pulley bases, four pulley towers, two C-clamps, and a mounting plate were manufactured by *Mancor Industries* at no charge while only providing two days lead time. All drawings used by *Mancor Industries* to produce these parts can be found under "*Appendix F – Calibration Jig Drawing Package*".

Once parts were received, Group MA02 made use of the MIG welder from the Undergraduate Project laboratory to weld the pulley towers to the pulley bases. Very little fixturing was required as both parts were designed and laser cut so they would interface at their respective corners/edges.

Mounting Post:

The only component that could not be laser cut by *Mancor Industries* was the mounting post pictured in *Figure 32* The mounting post needed to be turned down on a lathe, luckily this material was also provided to Group MA02 at no charge by *Mancor Industries*.

As seen in the engineering drawing for the mounting post (see "*Appendix F – Calibration Jig Drawing Package*"), the machining process was rather simple. The stock was placed into the lathe and the larger of the two diameters was brought down with low accuracy as it is not a critical tolerance. Once done, the locating feature of the post was brought down to size. With overall length being a critical dimension, as it must place the strain plate at the correct height relative to the pulleys, the component was cut from the stock via vertical band saw. Once done, the workpiece was placed back in the lathe to be faced down to the appropriate length.

The completed workpiece was then placed in the mill where eight concentric holes were drilled. Once done, the holes were tapped (by hand) to 5/16-18 UNC so that it could fasten the strain plate via bolts. With the strain plate attached, the mounting post and mounting plate were placed together on the weld table. The angle of the mounting post relative to the mounting plate was adjusted so that four of the strain plate spokes were perpendicular to the four sides of the mounting plate. Once finished, the mounting post was MIG welded to the mounting plate through the use of a MIG welder from the Undergraduate Project laboratory.

Again, the total cost to manufacture all components for the calibration jig (as well as obtaining stock) was $0 thanks to the McMaster Baja Team's sponsor, *Mancor Industries*.

Calibration Procedure:

Due to the simplicity and modularity of the jig, calibration was fairly easy and fast. Force would be incrementally applied while the DAQ system was logging. Several seconds of data was averaged at each force, which would correspond to a data point for all 6 axes in the calibration curve. This was repeated 6 times for each setup seen in Figure 34, after which the calibration results were processed.

Calibration Results:

The initial results seen after calibration had some cross axis coupling, so some further processing of the data was required. While this coupling is unfavourable, it is very linear, meaning the 6×6 coupling matrix could easily account for this and provide independent readings from each axis.

For a complete set of calibration curves, please see *"Appendix H – Calibration Curves"*.

After gathering the calibration data, the best fit slopes could be found from each axis for every possible input axis. This gives 36 slopes which represent the coupling rate relative to each axis. These can then be put into a 6×6 matrix but are still not useful to compute the decoupled forces and moments. Instead, the inverse of this matrix can be used to compute the decoupled forces from the original coupled ADC values.

Table 18: Final calibration matrix

	Fx	Fz	Fy	Mx	Mz	My
ADC 1	5.044492306	0.022798552	0.957260919	-0.856742101	-0.254252777	-1.318798296
ADC 2	-0.114543613	2.34750272	-0.056243943	0.168048506	-0.022629809	0.012281936
ADC 3	-1.020845682	-0.004561212	4.979181473	1.205404214	0.140116039	-0.823965288
ADC 4	1.176708427	0.006656985	0.084676972	8.534583741	-0.138213362	-0.708999787
ADC 5	-0.112056515	0.288942134	-0.054286697	0.020736229	-10.20482314	0.055168055
ADC 6	0.187744459	0.054555685	-1.068586883	-0.674597496	-0.071458224	-8.491673347

Since the calibration slopes were calculated relative to the input forces and moments, the decoupling matrix also serves as a calibration matrix, where the singular transformation to the measured ADC values will output the six decoupled force and moment values. The same original calibration tests were processed with the calibration and decoupling matrix to validate each axis. The resulting plot for the Z axis force is shown below in *Figure 34*. The rest other force and moment validation plots can be found under *"Appendix H – Calibration Curves"*.

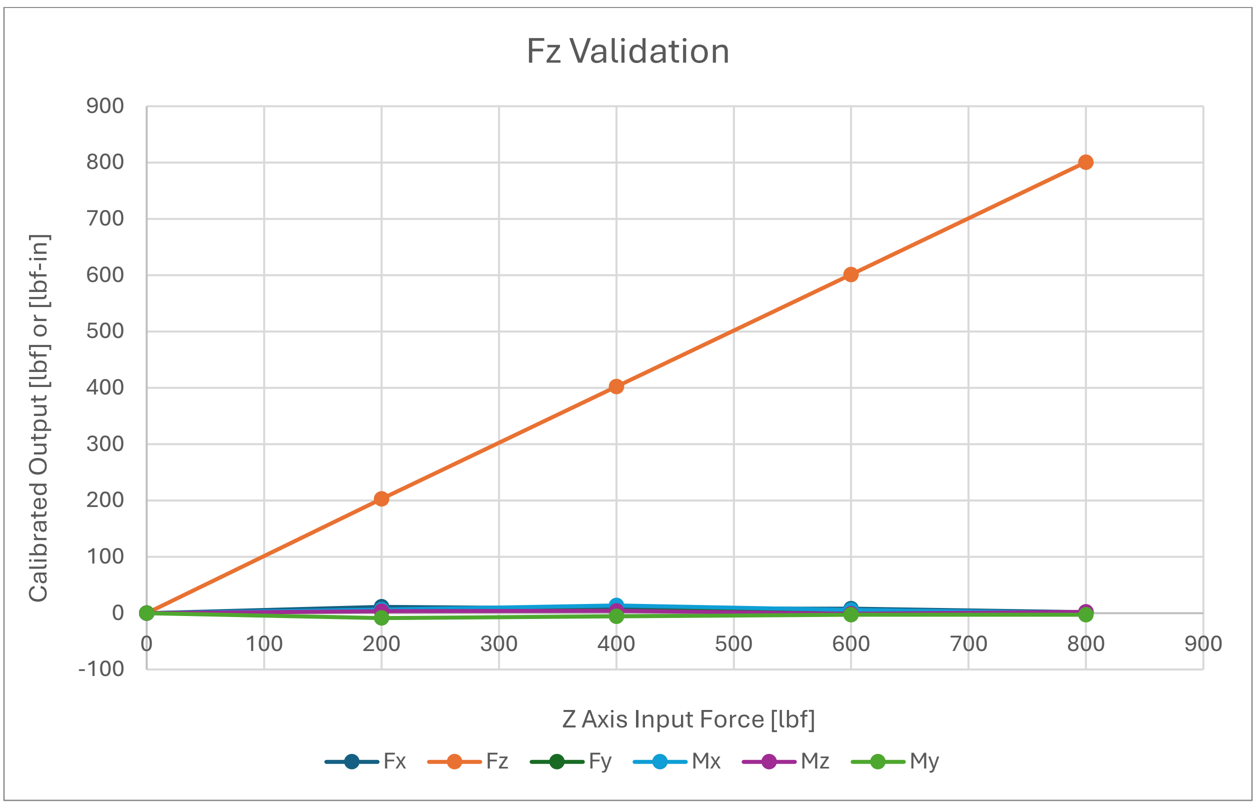

Figure 36: Validation plot for the Z axis force data.

With all six plots of the input calibration force/moment versus the output calibrated force/moment, the R^2 value of all six validation curves can be calculated to gauge the linearity of the WFT. A summary of the resulting R^2 values is shown below in *Table 19*.

Table 19: Summary of R^2 values for each force and moment axis.

R^2 value					
Fx	Fz	Fy	Mx	Mz	My
0.999893933	0.99998664	0.999898492	0.999906784	0.999814533	0.999915795

Field Tests & Results:

Finalized Product:

Figure 37: View of the WFT attached to the wheel of the Baja vehicle.

Results:

The McMaster Baja team's custom data viewer was used to process the data and plot forces and moments while displaying a synchronized video, seen in *Figure 38*. The team was able to see which obstacles were responsible for certain spikes in the data. These large impacts are then fed into SolidWorks FEA on the suspension assembly, where component design can be improved.

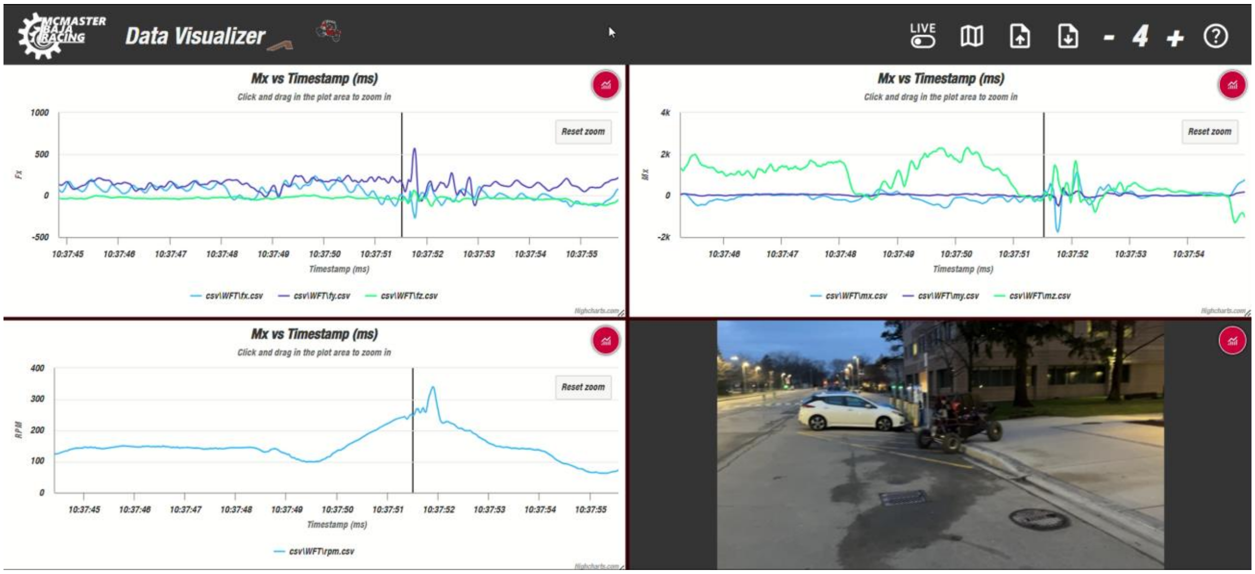

Figure 38:Snapshot of data viewer showing force graph outputs with corresponding video footage while driving over a curb.

Spending & Budget Report:

As discussed extensively in "*Background Research*" and "*Problem Analysis*", the cost of purchasing a WFT has been the largest barrier to the McMaster Baja Team (and other Canadian teams) from accessing this critical instrument. Because of this, Group MA02 set out to create an easy-to-follow design process, as well as a working WFT, while remaining within the Mechanical Engineering Department's $500 CAD budget. The hope was to create a WFT and design process that any Canadian team could replicate with limited funds.

As discussed heavily throughout this report, Group MA02 relied on the McMaster Baja Team, their sponsors, as well as manufacturing resources made available by the Department of Mechanical Engineering to meet this goal. These groups and services provided stock, licenses, electronic instrumentation, and much more.

Because of this, Group MA02 successfully created a WFT while remaining within the $500 CAD budget, as seen in this section. Note that while the overall project budget was met, the budget for certain subprojects/subcategories was exceeded - requiring the reallocation of funds from different areas as well as the purposefully (and conservatively) planned surplus. Nevertheless, Group MA02 not only sees this as an overall success but unavoidable hurdle in the budgeting of any engineering project.

Initial Budget:

Below, *Table 20* summarizes the initial budget outlined in the SoW document. This budget highlights a surplus/emergency fund of $100 CAD. Note that the budget was revised from the SoW document during the writing of the first term report. In this revision, the overall budget was increased by the department from $400 to $500 dollars and that additional $100 was put towards purchasing DAQ hardware. Secondly, finding that no sponsors could supply 7075-T6 stock, Group MA02 set aside $100 for its purchase.

Table 20: Proposed budget from SoW document. Note that the WFT stock budget was revised during the end of first term report.

Initial Scope of Work Budget			
WFT Body (Excludes all DAQ Components)			
Subcategory	Description	Allocated Budget (CAD)	Justification
WFT Stock	All material stock required for the strain plate, hub adaptor, and rim spacers.	-$100	Sponsors unable to supply cylindrical or plate stock of 7075-T6, will have to purchase off the shelf.
WFT Manufacturing Cost	Any fees paid to use or access manufacturing tools/machines to produce the strain plate, hub adaptor, and rim spacers.	$0	All machining will be on campus using one of three machine shops accessible to mechanical undergraduate students in JHE.
WFT Assembly	Materials such as fasteners or adhesives along with any speciality tools purchased for assembly.	$0	The McMaster Baja Team has granted access to use all their tools, fasteners, adhesives, etc. at no cost.
Software	CAD software used to design the WFT and to perform FEA tests.	$0	All members of the group have SolidWorks licenses provided through the McMaster Baja Team.
	Sub-Total	***-$100***	
DAQ Subsystem			
Subcategory	Description	Allocated Budget (CAD)	Justification
PCB Design and Fabrication	Cost to design and manufacture a single PCB without accessory hardware (i.e. processor).	$0	Supplied at no cost from McMaster Baja Sponsor PCBWay.
Strain Gauges	32 strain gauges required to emulate Feng's design [3].	-$50	Ali Express supplier intended to be used.
Hardware	Processor, batteries, switches, etc.	-$100	Possible to expense some, not all, from the McMaster Baja Team.
DAQ Housing	Any protective casings as well as mounting components.	$0	Intended to be 3D printed by Undergraduate Project Lab. Mounting accessories will be covered by the McMaster Baja Team.
DAQ Assembly	Tools (i.e. soldering iron), strain gauge mounting kit, wires, etc.	$0	The McMaster Baja Team has granted access to use all their tools and wiring. Strain gauge

			mounting kit available from Undergraduate Project Lab.
Software	Any software used to design PCB and process/display data.	$0	All required licensing software covered by the McMaster Baja Team or McMaster University.
	Sub-Total	***-$150***	
Testing and Calibration Jig			
Subcategory	Description	Allocated Budget (CAD)	Justification
Calibration Jig Stock	All material required to manufacture custom components for calibration jig.	$0	Intend to have stock covered by McMaster Baja sponsor's as well as the McMaster Baja Team.
Off-The-Shelf Components	Bearings, pulleys, cables, carabiners, etc.	-$150	Unable to justify purchases to sponsors.
Calibration Jig Assembly	Materials such as fasteners along with any speciality tools purchased for assembly.	$0	The McMaster Baja Team has granted access to use all their tools, fasteners, adhesives, etc. at no cost.
Software	CAD software used to design the custom components of the calibration jig.	$0	All members of the group have SolidWorks licenses provided through the McMaster Baja Team.
	Sub-Total	***-$150***	
Summary			
	Total Spending	***-$400***	
	Budget/Funding	***+$500***	
	Surplus	***+$100***	

Spending Report:

WFT Body Spending Report:

Table 21 below shows an in-depth spending report pertaining to the WFT body. Though the majority of budget goals were met, Group MA02 exceeded the budget on stock by $22.49 CAD. As seen above in the previous table, the surplus of $100 CAD can be used to cover this.

Table 21: Summary of spending on WFT body shows a deficit of $22.49.

WFT Body Spending Report			
WFT Stock			
Item	Description	Supplier	Cost (CAD)
Strain Plate Stock	10in×10in×½in 7075-T6 stock	Golden Triangle Specialty Metals	-$60.342

Hub Adaptor Stock	6.5in diameter (1.5in length) 7075-T6 stock	Golden Triangle Specialty Metals	-$62.15
Rim Spacers	1in diameter (3in length) 7075-T6 stock	McMaster Baja Team	$0
		Subtotal	***-$122.49***
		Allotted Budget	***$100***
		Deficit	***-$22.49***
WFT Manufacturing Cost			
Item	Description	Supplier	Cost (CAD)
Strain Plate	Water-jetting and CNC milling	1ST floor JHE Machine Shop	$0
Hub Adaptor	Turning process on manual lathe and cutting, drilling, reaming on 3-axis manual mill performed by members of Group MA02	Undergraduate Project Lab / Machine Shop	$0
Rim Spacers	Turning and drilling process on manual lathe performed by members of Group MA02	Undergraduate Project Lab / Machine Shop	$0
		Subtotal	***$0***
		Allotted Budget	***$0***
		Surplus	***$0***
WFT Assembly			
Item	Description	Supplier	Cost (CAD)
5/16-18 UNC Fasteners	Fasteners to attach strain plate to hub adaptor (×8) and corresponding washers	McMaster Baja Team	$0
3/8-16 UNC Locknuts	Locknuts to attach hub adaptor to threaded studs of hub (×4) and corresponding washers	McMaster Baja Team	$0
		Subtotal	***$0***
		Allotted Budget	***$0***
		Surplus	***$0***
Summary of WFT Body Spending			
		Total Spending	***-$122.49***
		Allotted Budget	***$100***
		Deficit	***-$22.49***

DAQ Subsystem Spending Report:

Table 22 below details the largest deficit (-$137.45 CAD) of all three sub-budgets. Though this is initially alarming, the set aside surplus as well as the unexpected savings from the testing and calibration jig, allow Group MA02 to remain within their overall budget of $500 CAD. For a detailed expense report, refer to "*Appendix G – Purchase Order Form*."

Table 22: Summary of spending on DAQ subsystem shows a deficit of $137.45.

DAQ Subsystem Spending Report

PCB Design and Fabrication			
Item	Description	Supplier	Cost (CAD)
Altium License	Software package to design PCBs	McMaster Baja Team	$0
PCB Fabrication	Two-layer PCB	PCBWay	$0
		Subtotal	***$0***
		Allotted Budget	***$0***
		Surplus	***$0***

Strain Gauges			
Item	Description	Supplier	Cost (CAD)
Strain Gauges (qt of 120)	BF350-3AA Strain Gauges, extra purchased due to high probability of poor quality and failure to mount.	Ali Express	-$25.92
		Subtotal	***-$25.92***
		Allotted Budget	***$50***
		Surplus	***$24.08***

Accessory Hardware for PCB			
Item	Description	Supplier	Cost (CAD)
Power Switch (qt 3)	Rocker switch (SPST, 6A, 125V) used to toggle Wi-Fi and power.	Digi-Key	-$7.95
Processor	TEENSY 4.1 processor without ethernet	Digi-Key	-$44.51
Threaded Inserts (qt 20)	M3 X 0.5 insert for wire management and routing	Digi-Key	-$5.38
LED Kit	LED selection kit of various colours	Digi-Key	-$10.61
RF Antenna (qt 2)	Wi-Fi antenna to transmit data from PCB to computer.	Digi-Key	-$32.42
Coaxial Cable (qt 3)		Digi-Key	-$8.37
Potting Material	375ml of black urethane potting to secure strain gauges	Digi-Key	-$122.20
Battery (qt 2)	Lithium polymer batteries	McMaster Baja Team	$0
		Subtotal	***-$261.53***
		Allotted Budget	***$100***
		Deficit	***-$161.53***

DAQ Housing			
Item	Description	Supplier	Cost (CAD)
Reinforced Nylon Spool	Single spool of reinforced nylon for 3D printing of DAQ housing and lid.	McMaster Baja Team	$0
3D Printing	Time and access allotted to use 3D printer to manufacture DAQ housing.	McMaster Baja Team	$0
		Subtotal	***$0***
		Allotted Budget	***$0***
		Surplus	***$0***

DAQ Assembly

Item	Description	Supplier	Cost (CAD)
Strain Gauge Mounting Kit	Kit includes specific surface prep and adhesive tools	Undergraduate Project Lab	$0
Specialty Electrical Tools	Soldering irons, solder, helping hands, heat gun etc.	McMaster Baja Team	$0
Wires	Various gauge and length of electrical wires	McMaster Baja Team	$0
		Subtotal	***$0***
		Allotted Budget	***$0***
		Surplus	***$0***
Summary of DAQ Subsystem Spending			
		Total Spending	***-$287.45***
		Allotted Budget	***$150***
		Deficit	***-$137.45***

Testing and Calibration Jig Spending Report:

Contrary to the spending of the DAQ subsystem, Group MA02 was able to produce a surplus of $103.05 CAD when developing the calibration jig. In combination with the emergency surplus set aside at the beginning of budgeting, the overall budget goal of $500 CAD was met.

Table 23: Summary of spending on testing and calibration jig shows a surplus of $103.05.

Testing and Calibration Spending Report			
Calibration Jig Stock and Machining			
Item	Description	Supplier	Cost (CAD)
½in Steel Plates	Unknown quantity delivered to team manufactured by sponsor	Mancor Industries	$0
Laser Cutting	Sponsor laser cut all ½in plates into desired geometries for calibration jig	Mancor Industries	$0
Mounting Post Stock	4in diameter (4in length) carbon steel stock	McMaster Baja Team	$0
Manufacturing of Mounting Post	Simple turning and parting process on manual lathe performed by Group MA02	Undergraduate Project Lab	$0
Pulley Profiles	PLA and access to 3D printer to print pulley profiles to be pressed over bearings	Undergraduate Project Lab	$0
		Subtotal	***$0***
		Allotted Budget	***$0***
		Surplus	***$0***
Off-The-Shelf Components			
Item	Description	Supplier	Cost (CAD)
Cable Pack	20 feet of ¼in steel cable, four carabiners, and various cable ties.	Home Depot	$28.45

Bearing (×2)	R6ZZ shielded bearing with 3/8in bore to be pressed into printed pulley profiles	Amazon	$18.50
		Subtotal	***-$46.95***
		Allotted Budget	***$150***
		Surplus	***$103.05***
Calibration Jig Assembly			
Item	Description	Supplier	Cost (CAD)
Weld Table	Weld table to mount calibration jig to	Hatch Workshop	$0
Fixture Pins	Used to clamp calibration jig to weld table	Hatch Workshop	$0
3/8-18 UNC Fasteners (×8)	Various length 3/8-18 UNC fasteners used to attach C-clamps to dummy rim as well as pulleys to respective towers	McMaster Baja Team	$0
Crane Scale (×2)	Used to measure applied load to calibration jig	McMaster Baja Team	$0
Various Scrap Steel	Used to load weighted buckets and measured with crane scales	McMaster Baja Team	$0
		Subtotal	***$0***
		Allotted Budget	***$0***
		Surplus	***$0***
Summary of Testing and Calibration Jig Spending			
		Total Spending	***-$46.95***
		Allotted Budget	***$150***
		Surplus	***$103.05***

Summary of Spending Report:

Table 24 summarizes the spending of each sub-budget found above in *Tables 21, 22, and 23*. It is easy to see from this table that Group MA02 was not only able to remain within the $500 CAD budget but produce a surplus of $43.11 CAD. This exceeded the initial goal of what was defined as an affordable and cost-effective WFT.

Table 24: Summary of project spending indicates that Group MA02 outperformed their desired budget of $500, creating a surplus of $43.11.

Summary of Project Spending			
Sub-Budget	*Budget (CAD)*	*Spending (CAD)*	*Surplus/Deficit (CAD)*
WFT Body	$100	-$122.49	-$22.49
DAQ Subsystem	$150	-$287.45	-$137.45
Testing and Calibration Jig	$150	-$46.95	$103.05
Emergency Funds/Surplus	$100		
Total	$500	-$456.89	$43.11

Project Completion Status:

The following section serves as a summary to the reader to quantify the success of this project relative to the initial objectives highlighted in the scope of work document as well as those refined in the first term report.

This section does not cover how these were met, as this is covered extensively in writing, figures, and tables throughout "*Final Design & Fabrication*", "*Calibration*", as well as "*Field Test & Results*". Additionally, this section does not include budgeting constraints and objectives as this was discussed under *"Spending & Budget Report"*.

Table 25 highlights that all objective pertaining to Group MA02's capstone have been met prior to the delivery date of this report and its corresponding presentation. It is Group MA02's belief that they have successfully created an affordable WFT that is compatible with the McMaster Baja Racing Team car.

Table 25: All constraints and objectives relating to Group MA02's capstone have been met while remaining within the $500 CAD budget.

Project Completion Status			
Constraint/Objective	Final Product Value (if applicable)	Was it Met?	Notes:
Transducer Body Design			
Overall mass under 6lbs including fasteners, DAQ system and DAQ housing.	3lbs and 2oz	Yes	Completed at nearly half the stated weight
Lifespan of 896, 000 cycles (maximum endurance limit of 240MPa) with 100lbf fully reversible load	1,250,00 cycles	Yes	Suspected life span generated from SOLIDWORKS FEA
Minimum fast fracture FOS (Von Mises) of 1.25 with 1000lbf radial load and 500lbf lateral load	2.26	Yes	Suspected FOS from SOLIDWORKS FEA likely higher than what was reported
Manufacturable with available lab infrastructure on campus	NA	Yes	Completed with water jet, CNC mill, manual mill, manual lathe
All DAQ equipment and housing mountable onto strain plate	NA	Yes	N/A
Mountable to the Baja car's four-stud hub	NA	Yes	NA
Fits within Baja car's rim with no protrusion	NA	Yes	NA
Testing and Calibration Jig			
All three-force axis calibration curves produce $r \geq 0.9$	$r_{min} = r_{F_x} = 0.99989352$	Yes	NA

All three moment axis calibration curves produce $r \geq 0.9$	$r_{min} = r_{M_z} = 0.999811917$	Yes	NA
Transducer can withstand four hours of field testing	4 hours	Yes	NA
Known loads applied to WFT for each of the three force and three moment axes	NA	Yes	NA
Calibration jig mountable to weld table	NA	Yes	N/A
All nonmachined components of jig purchased off the shelf	NA	Yes	Bearings and steel cables included
Manufactured with available lab and sponsor infrastructure	NA	Yes	Completed with a manual lathe and laser cutter.
DAQ Software and Hardware			
Output 1×6 strain vectors denoted as $\overline{\boldsymbol{S}} = \left[S_{F_x}, S_{F_y}, S_{F_z}, S_{M_x}, S_{M_y}, S_{M_z}\right]$	NA	Yes	NA
Integration with the team's data viewer to output $\overline{\boldsymbol{F}} = \left[F_{F_x}, F_{F_y}, F_{F_z}, F_{M_x}, F_{M_y}, F_{M_z}\right]$	NA	Yes	Na
Sample all strain gauges at 1kHz	1kHz	Yes	NA
Data saved on micro-SD card and transmitted via Wi-Fi	NA	Yes	NA
Software developed entirely with available numerical tools	NA	Yes	Excel, Matlab and VSCode used for all software development
Output data in CSV format	NA	Yes	N/A
Manufacturable by PCBWay	NA	Yes	Done for $0
DAQ housing components can be 3D printed	NA	Yes	Reinforced nylon spools used

Unanticipated Milestones:

Aside from the milestones and constraints highlighted above in *Table 25* from the scope of work document, a few unanticipated milestones/challenges were encountered.

Use of Turnbuckles on the Calibration Jig:

Initial results from the calibration jig were very promising, however Group MA02 was limited in the amount of weight that could be applied based on available steel scrap as well as the strength of the construction buckets. In order to create a larger calibration curve (in turn creating a more accurate WFT), Group MA02 decided to utilize turn buckles to reach 800lbf of loading as seen below in *Figure 39*.

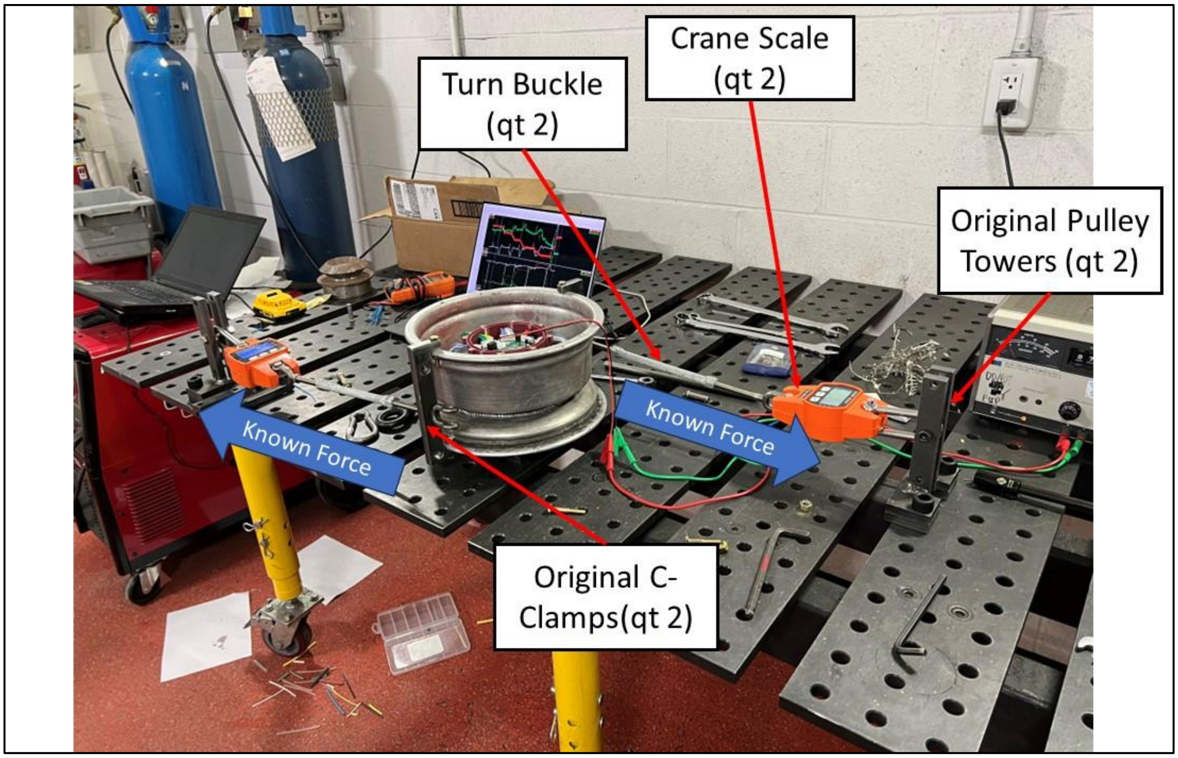

Figure 39: Turnbuckles are employed to input forces exceeding 800lbf, putting the WFT above into torsion. Note that the pulley towers and C-Clamps are the same ones used with the weighted construction buckets.

The use of turnbuckles required no additional manufacturing; the same pulley towers, C-Clamps, and mounting posts used for the original calibration jig are still employed. Instead, as seen above in *Figure 39,* the turnbuckles are connected to the C-Clamps and crane scales, and the crane scales are connected to the pulley towers. To input a force, the turnbuckle is tightened so that the connecting arms shorten. Both turnbuckles are set to the same desired force by tightening them until the desired force pound reading is met on each crane scale. This setup was used in conjunction with the weighted buckets to create the calibration curves seen "*Calibration Results"*.

Additional Protective Casings for DAQ System:

Once the WFT was attached to the Baja car, it became clear that some of the DAQ system was too exposed to the environment in order for the group to feel confident that it would withstand the conditions it would be exposed to while being driven. For this reason, the group designed an additional cover plate that encloses the entirety of the WFT, thereby shielding it from any flying debris or dirt. This new cover, which was 3D printed for no additional cost using materials already available to the group, is shown in *Figure 40*. Included in this design, two simple on/off switches were added to make the testing process easier once the transducer is attached. One switch controls the power to the WFT and the other turns on or off the Wi-Fi.

Figure 40: View of the WFT mounted to the wheel of the car, showing the new 3D printed cover, added to protect the WFT's DAQ system from any dirt or debris while the car is driving.

Future R&D Recommendations:

Calibration Jig:

The use of turnbuckles to input a force on the calibration jig was more than promising. In fact, it is debatably better than suspending mass, as fewer components, such as the mass itself, cables, and cable ties, are required.

However, the calibration jig that was designed only holds the WFT in a specific orientation. Because of this, the WFT had to be fixed to the table with impromptu methods that can be seen in *Figure 41*. Though these fixation methods are still adequate, they are not standardized and would be difficult to recreate. In the future, Group MA02 suggests the McMaster Baja Team redesigns the calibration jig so that the WFT can be reoriented to the specific positions that the turnbuckles require. Such a solution would allow the McMaster Baja Team to create calibration curves with more data points.

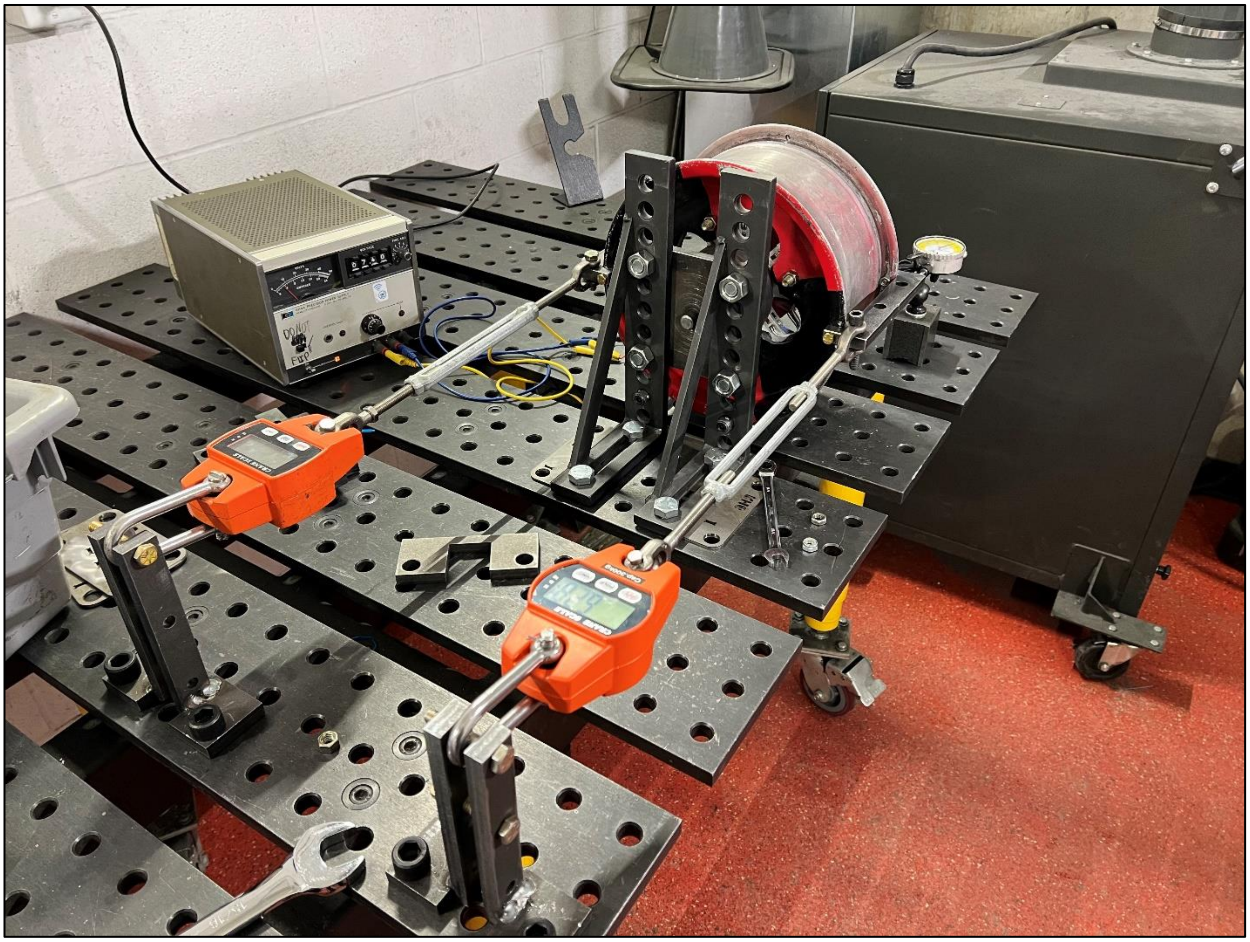

Figure 41:The WFT is turned 90 degrees as the mounting post is fixed to 90-degree fixture brackets. A dial indicator is used to assure it is level in this somewhat precarious setup.

Strain Gauge Selection:

In retrospect, Group MA02 was very lucky with the strain gauges purchased from an unknown foreign supplier at a heavily discounted price from the industry standard. It was expected that many of the strain gauges would not create accurate results, would fail prematurely, or fail to adhere to the WFT – hence the purchase of 120 strain gauges instead of the required 32. Instead, the risk with the unknown provider of strain gauges provided very few challenges.

However, in the future, Group MA02 recommends that the McMaster Baja Team acquires a sponsor that can provide the required 32 strain gauges. Such a sponsor would be able to provide strain gauges that contain proper documentation and were produced in accordance with any applicable codes/standards. Though buying strain gauges is another option, the purchasing of 32 of them at market price is likely out of the budget for the McMaster Baja Team.

References

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[2] webdev, "MTU Baja Enterprise Wheel Force Transducer Testing," 4 September 2018. [Online]. Available: https://www.michsci.com/mtu-baja-testing/. [Accessed 2 October 2023].

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[4] MTS Systems Corporation, *SWIFT® 10 ATV Sensor Product Information,* MTS Systems Corporation, 2008.

[5] G. A. Kebede, A. R. Ahmad, S.-C. Lee and C.-Y. Lin, "Decoupled Six-Axis Force–Moment Sensor with a Novel Strain Gauge Arrangement and Error Reduction Techniques," *Sensors (Basel),* vol. 19, no. 13, 2019.

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[7] M. Samatham, R. P. Naik, B. R. H. Reddy and G. A. Kumar, "A Study on Improvement of Fatigue Life of materials by Surface Coatings," *International Journal of Current Engineering and Technology,* vol. 8, no. 1, January 2018.

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[9] Federal Agencies Digital Guidelines Initiative, *Term: Sampling rate (audio),* Digitization Guidelines.

[10] M. J. J. Donachie, Titanium: A Technical Guide, Metals Park, Ohio: ASM International, 1988, p. 11.

[11] MatWeb, *Titanium Beta C, Aged 565°C,* MatWeb: Material Property Data.

[12] ASM Aerospace Specification Metals Inc., *Aluminum 7075-T6; 7075-T651,* MatWeb.

Appendix A – Wheel Force Transducer Quotes:

MTS Systems Corporation:

Caution: External email.

Hi [redacted]

Thanks for your inquiry – I am the local MTS sales contact for Central & Eastern Canada.

Please see as follows some information and comments on our SWIFT products:

- For light vehicles such as would be found in the Baja SAE competition, (similar to a small/medium ATV), the SWIFT 10T should be suitable. Please see the attached SWIFT 10 manual and performance specs tabl for more detail.
- ROM / Rough order of Magnitude pricing for just one sensor, Mini-TI box, and cables is going to be approximately USD $110k. I realize this may be price prohibitive for your team. You will also need a laptop PC and a data acquisition system capable of at least 7 channel, 10V full-scale analog measurements. We don't sell the DAQ systems, but do recommend vendors that have been used successfully with our products. Standard cables terminate with BNC connections at the data acquisition end.
- Minimum rim size is listed as 177.8mm on our website, but this is for the standard configuration where the SWIFT is mounted within the rim. There are some other clever configurations that can get around this but there are other tradeoffs such as lower force ratings due to moment loading, etc.

If you're interested in learning more, we would be happy to have a conversation about wheel force transducers in general, or other ways to measure forces at the wheel that are lower cost options.

Best Regards,

[redacted]

[redacted]

MTS Systems Corporation
(613) [redacted]

Figure 42: $110,000 (USD) quote from MTS for a wheel force transducer for the McMaster Baja Team.

Michigan Scientific Corporation:

Hello [redacted]

I see you have inquired about the price of a Wheel Force Transducer (WFT). The purchase price is about $75,000 USD for one corner.

We do a free loan to University Baja and Formula teams on 1 WFT kit. However now we have a long queue, so it would probably be next summer before you could get the loaner kit. Would you like us to add you to the queue?

Here is a video of a Baja team using the WFT.

https://www.youtube.com/watch?v=56wuhRjExJQ

Regards,

--
[redacted]
Wheel Force Transducer Systems
Vice President
Michigan Scientific Corporation
[redacted]

Figure 43: $75 000 (USD) quote from Michigan Scientific for a wheel force transducer for the McMaster Baja Team.

Appendix B – Wheel Force Transducer Specification Sheets:

MTS Systems Corporation:

SWIFT 10 ATV Transducer Performance (part 1 of 2)

PARAMETER	SPECIFICATION	
Use		
SWIFT 10 ATV (aluminum) for:	low weight, high sensitivity, lower measured forces	
SWIFT 10 ATV (titanium) for:	high fatigue life, longer durability, higher loads	
Maximum usable rpm	2,200	
Maximum speed	250 kph (155 mph)	
Shock resistance, each axis	150 G	
Fits rim size (usable range)	7-12 inch*	
Number of Lug nuts accommodated	4	
Hub bolt circle diameter accommodate	All	
Wheel stud size accommodated	All	
Input voltage required	9–30 V DC	
Input power required per transducer	7 Watts maximum (22 Watts typical)	
Output voltage ± full scale calibrated load	±10 V †	
SAE J328	**Aluminum**	**Titanium**
Rated load capacity‡	2.5 kN (550 lbf)	4.2 kN (925 lbf)
Bending moment§	1.45 kN•m (12 869 lbf•in)	4.76 kN•m (42117 lbf•in)
Full scale calibrated ranges	Consult the calibration range sheet that accompanies each transducer	
Resolution	Infinite	
Performance accuracy		
Nonlinearity	1.0% full scale	
Hysteresis	0.50% full scale	
Modulation	≤5.0% reading	
Cross talk#	1.5% full scale	
Maximum operating temperature**	125°C (257°F	
Assembly Weight – single wheel		
Transducer	1.4 kg (3.0 lb)	2.0 kg (4.5 lb)
Aluminum hub adapter/spacer	0.5 kg (1.0 lb)	0.5 kg (1.0 lb)
Slip ring assembly	0.5 kg (1.1 lb)	0.5 kg (1.1 lb)
Modified aluminum rim	2.4 kg (5.3 lb)	2.4 kg (5.3 lb)
Lug nuts	0.1 kg (0.2 lb)	0.1 kg (0.2 lb)
Outer steel washer plate	0.2 kg (0.4 lb)	0.2 kg (0.4 lb)
Attached fasteners	0.8 kg (1.8 lb)	0.8 kg (1.8 lb)
Total	5.8 kg (12.8 lb)	6.5 kg (14.3 lb)

Figure 44: Spec sheet for SWIFT 10 ATV wheel force transducer showing a total weight of 5.8kg (12.8lbs).

Michigan Scientific Corporation:

Specifications

Maximum Recommended Static Weight [Fz]	1,200 lb (550 kg)
Maximum Force Capacity [Fx,Fz] (radial)	5,600 lbf (25 kN)
Maximum Force Capacity [Fy] (lateral)	2,000 lbf (8.9 kN)
Maximum Torque Capacity [Mx, Mz]	1,500 lbf · ft (2.0 kN · m)
Maximum Torque Capacity [My]	2,500 lbf · ft (3.4 kN · m)
Accelerometer Range	± 100 g
Nonlinearity [Fx,Fy,Fz,My]	≤ 0.25 % of full scale output
Nonlinearity [Mx,Mz]	≤ 0.50 % of full scale output
Hysteresis	≤ 0.25 % of full scale output
Crosstalk After Correction	≤ 0.4 % of full scale output
Temperature Range, Operating	-40 °F to 257 °F (-40 °C to 125 °C)
Angular Resolution	0.17° (slip ring) 0.25° (telemetry)
Transducer Mass	3.2 lb (1.5 kg)

Figure 45: Spec sheet for LW25 wheel force transducer showing a total weight of 1.5kg (3.2lbs).

Appendix C – Material Stock Quotes:

GOLDEN TRIANGLE SPECIALTY METALS LTD.

471 Dundas St. N
Cambridge ON N1R 5R6
Ph. (519) 623-5500 Fax (519) 623-5745

Quote

Q000194994

Date November 23, 2023
Customer CASH

Bill To:
Cash Sales

Ship To:
Cash Sales

PO Number	F.O.B.	Salesperson	Order Date	Order Number
McMaster Baja Racing	our dock	Shawn	23-Nov-2023	Q000194994

Ship Via	Payment Terms	Reference
Pick Up	C.O.D.	

Part Number	Description	UOM	Ordered	Unit Price	Extended Price
AP05481447075	1/2" 7075-T6 Plate 10 x 10	SQI	100	0.53	53.40
AR65/7075	6 1/2"dia 7075-T6	IN	6.5	39.58	257.29

	Net Amount	310.69
102138344RT0001	Ontario HST	40.39
	Total Due	**351.08**

Figure 46:Quote from local supplier, Golden Triangle, for 7075-T6 aluminum stock.

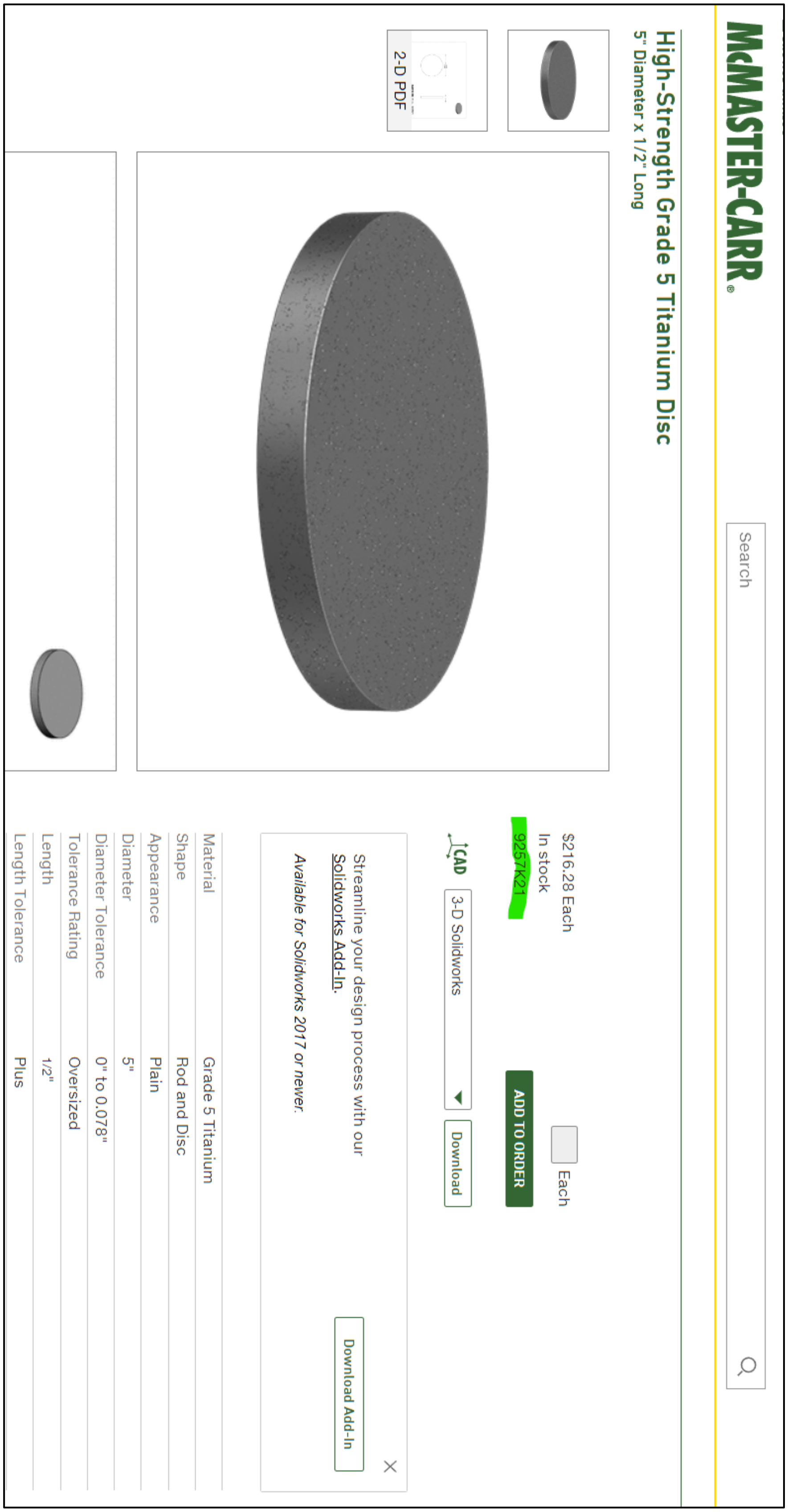
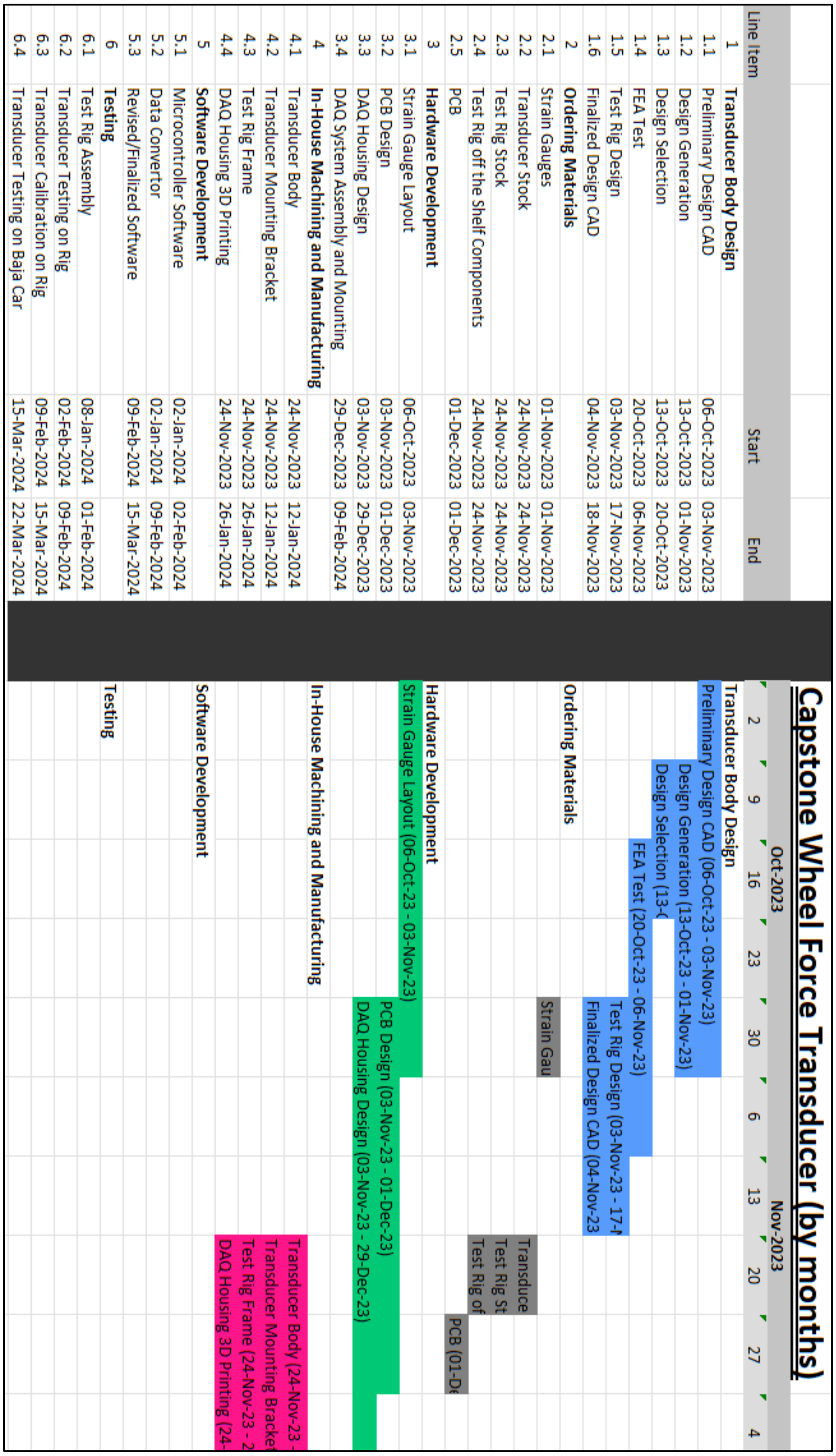
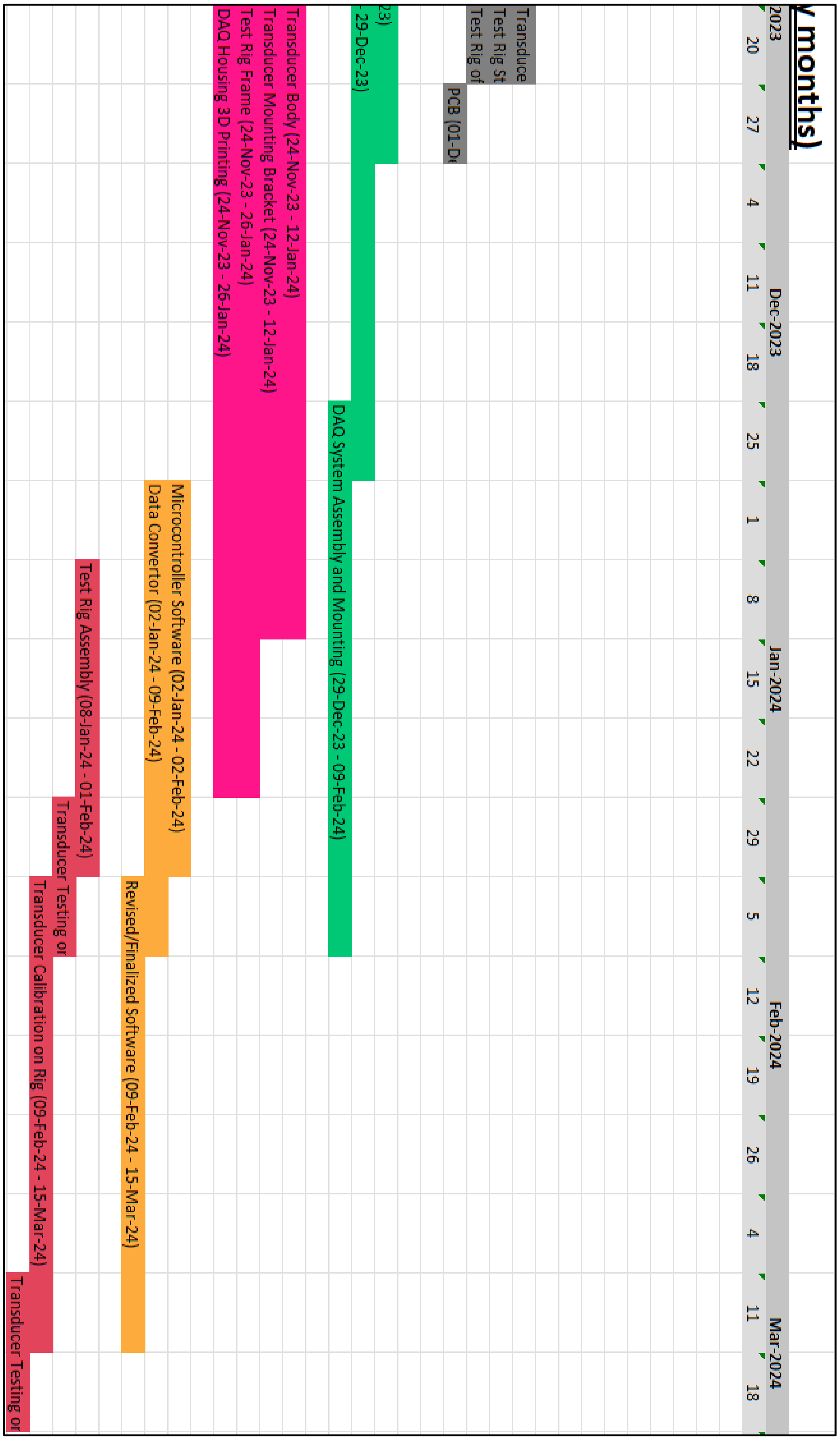


Figure 47: McMaster-Carr was the cheapest source the group could find for titanium, at $216.23 USD.

Appendix D – Gantt Chart:




months)
2023
Dec-2023
Jan-2024
Feb-2024
Mar-2024
20 27 4 11 18 25 1 8 15 22 29 5 12 19 26 4 11 18
DAQ System Assembly and Mounting (29-Dec-23 - 09-Feb-24)
Transducer Body (24-Nov-23 - 12-Jan-24)
Transducer Mounting Bracket (24-Nov-23 - 12-Jan-24)
Test Rig Frame (24-Nov-23 - 26-Jan-24)
DAQ Housing 3D Printing (24-Nov-23 - 26-Jan-24)
Microcontroller Software (02-Jan-24 - 02-Feb-24)
Data Convertor (02-Jan-24 - 09-Feb-24)
Revised/Finalized Software (09-Feb-24 - 15-Mar-24)
Test Rig Assembly (08-Jan-24 - 01-Feb-24)
Transducer Calibration on Rig (09-Feb-24 - 15-Mar-24)

Appendix E – WFT Body Drawing Package:

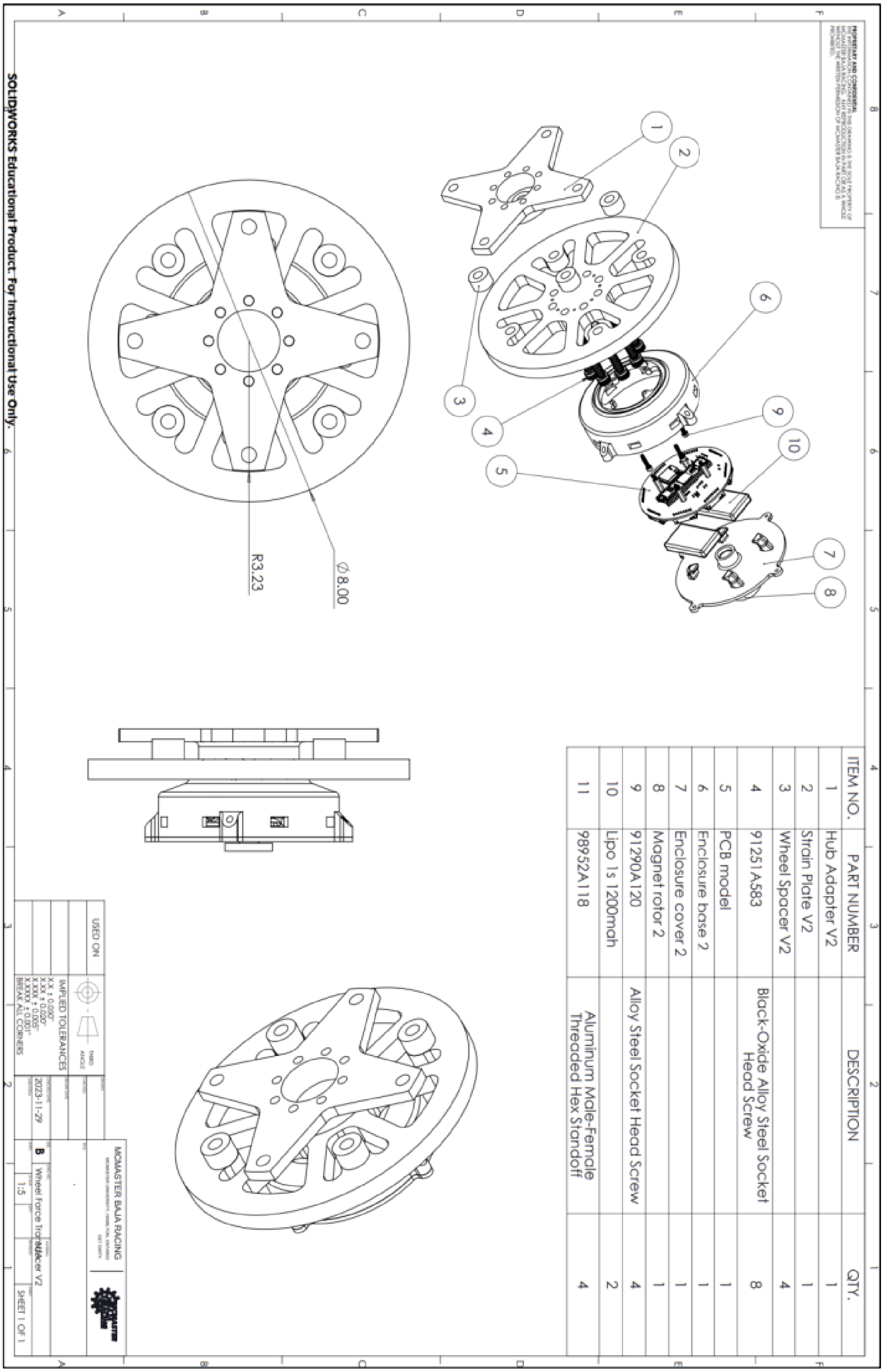


Figure 48: Assembly Drawing of Finalized WFT Design including renderings of the DAQ system.

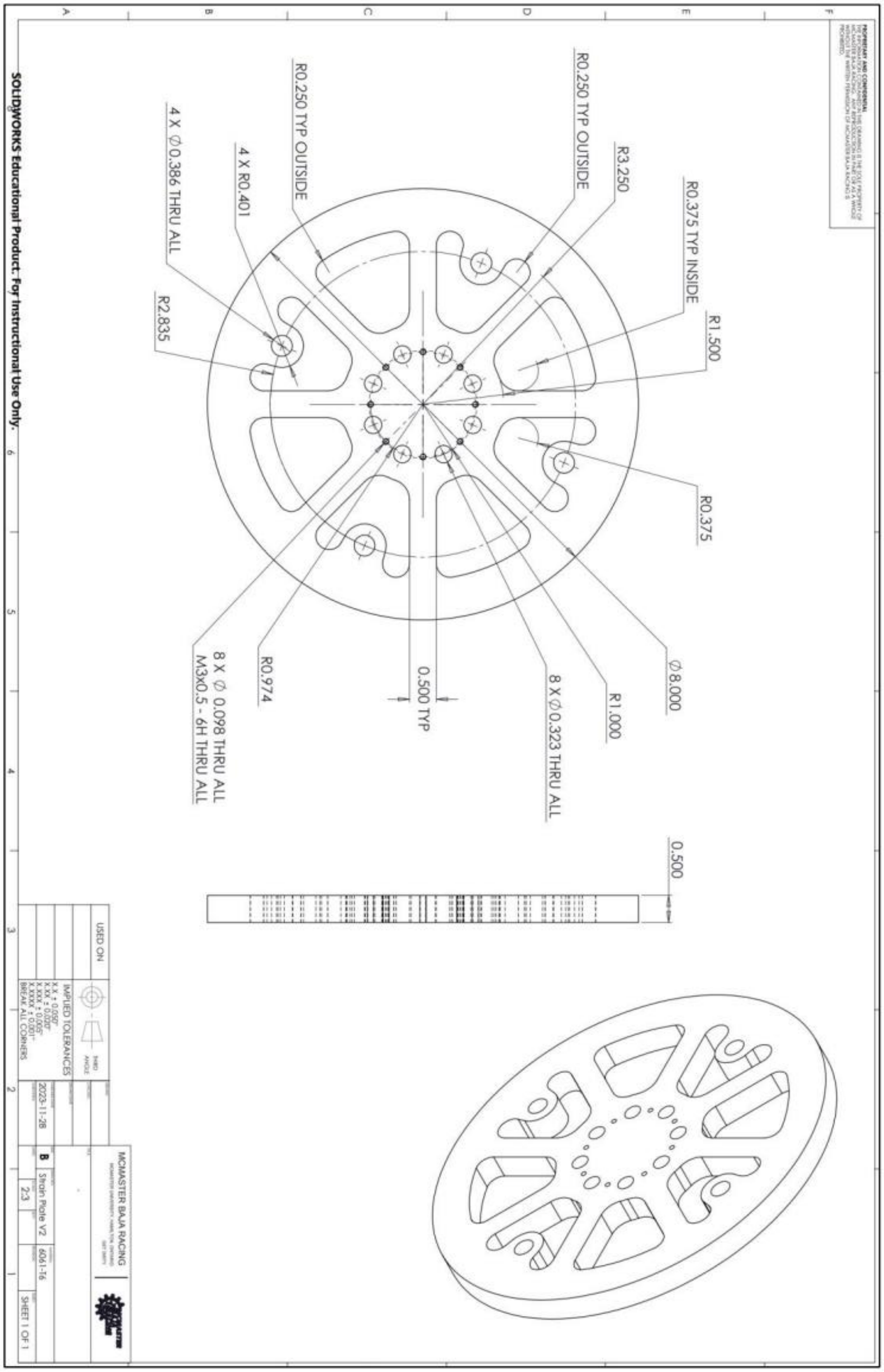


Figure 49: Drawing of the 7075-T6 strain plate.

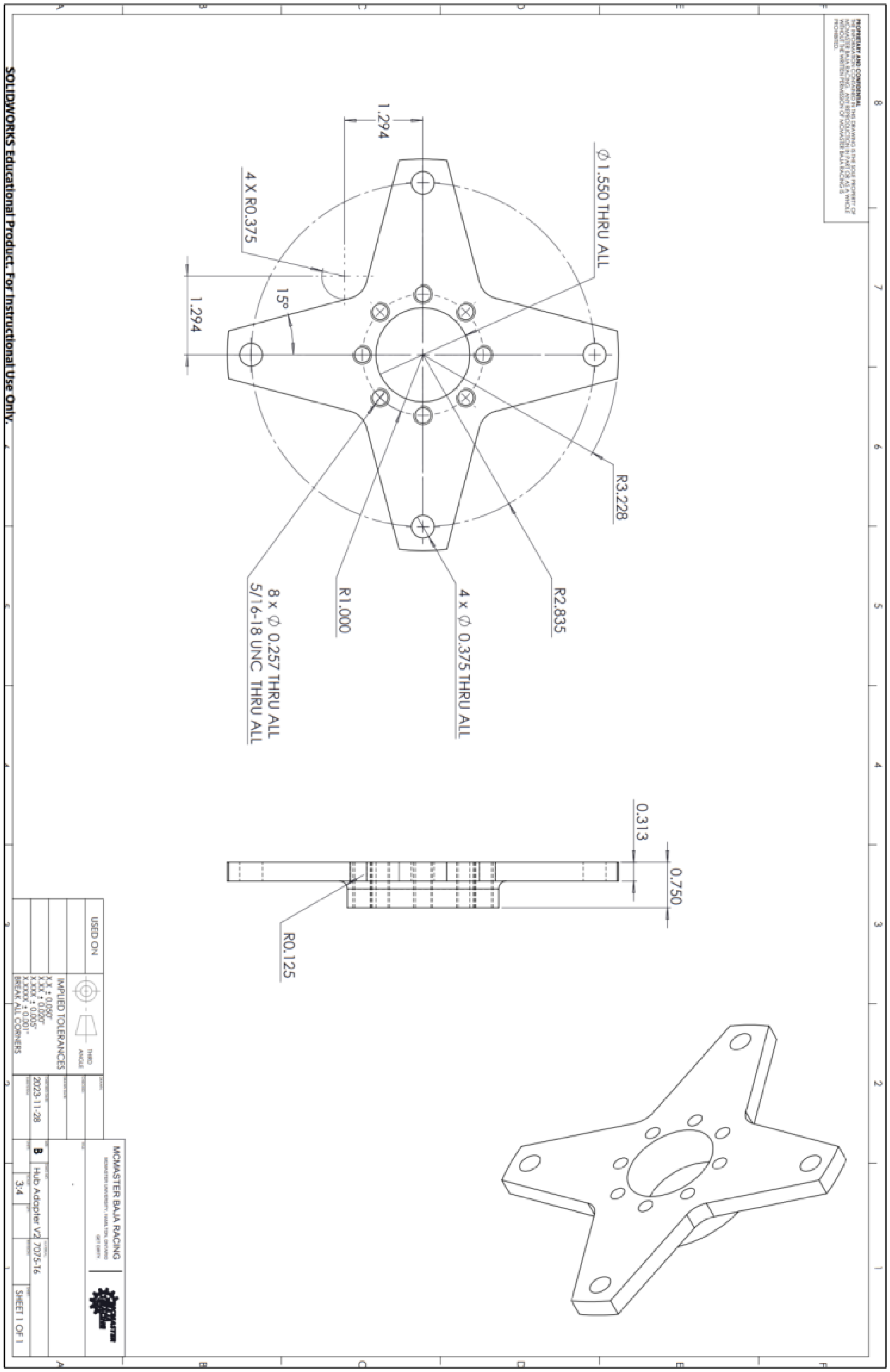


Figure 50: Drawing of the 7075-T6 hub adaptor.

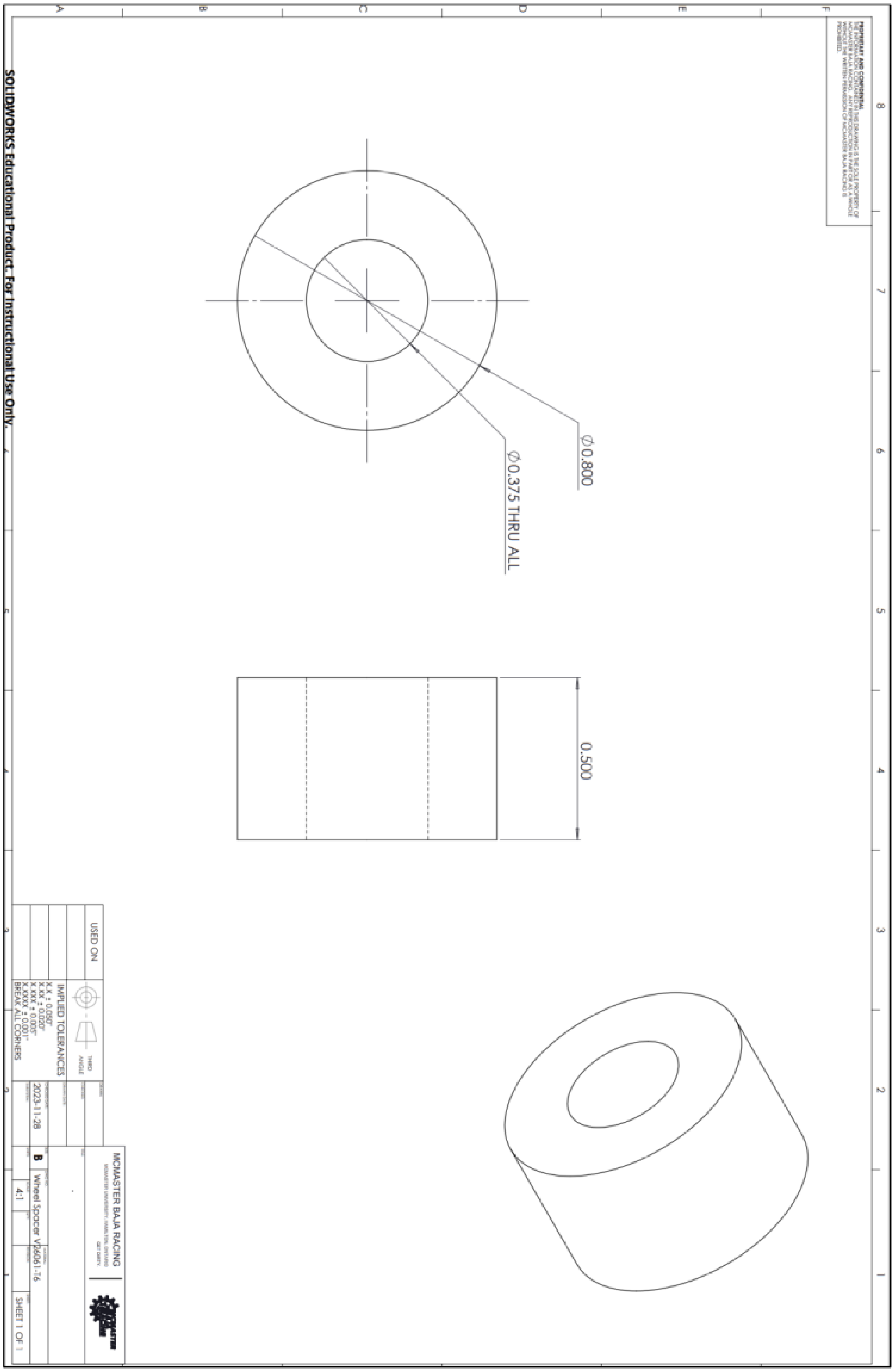


Figure 51: Drawing of 7075-T6 wheel spacers.

Appendix F – Calibration Jig Drawing Package:

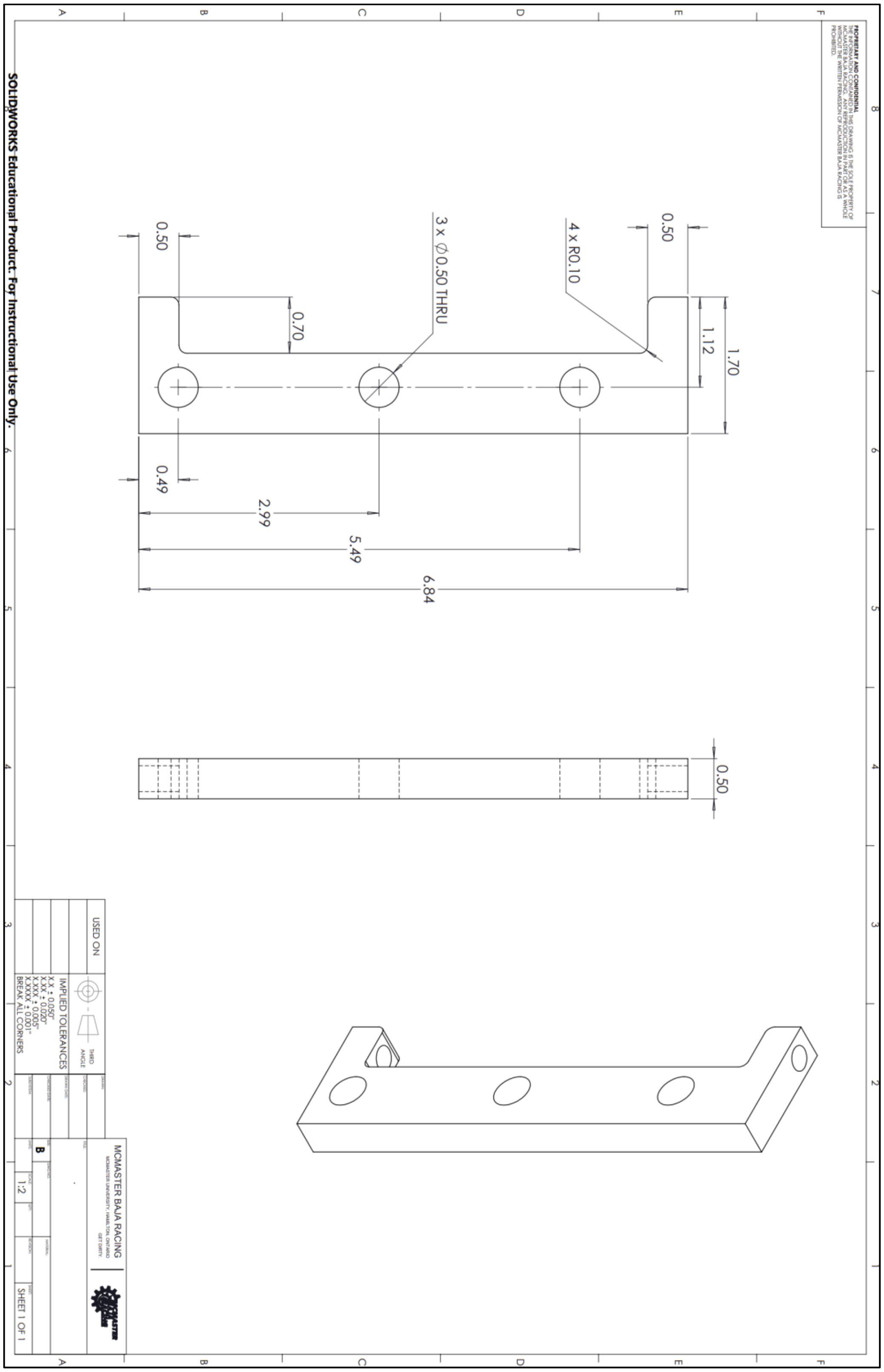


Figure 52: Drawing of C Clamp Post.

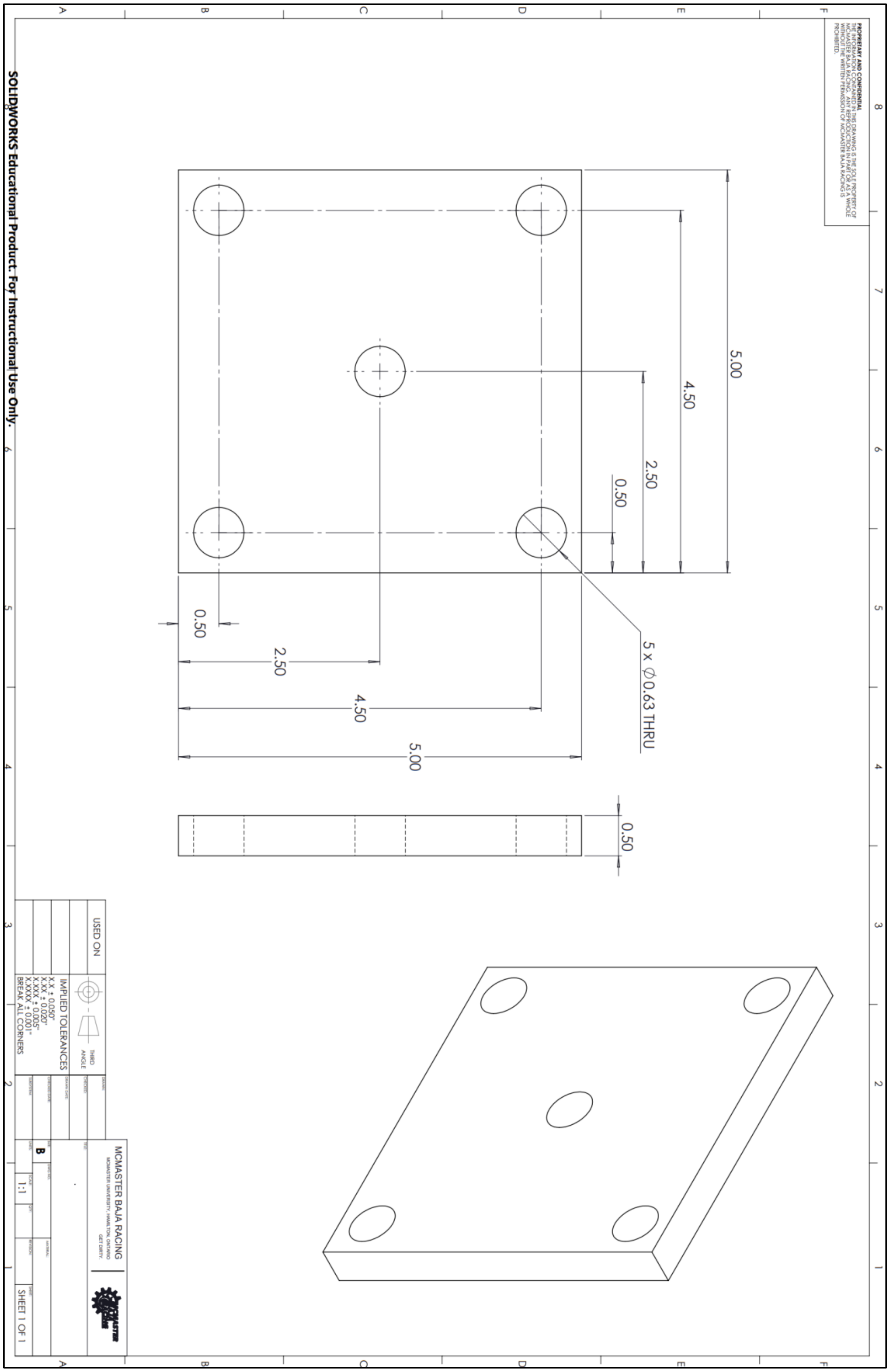


Figure 53: Drawing of Primary Mounting Plate.

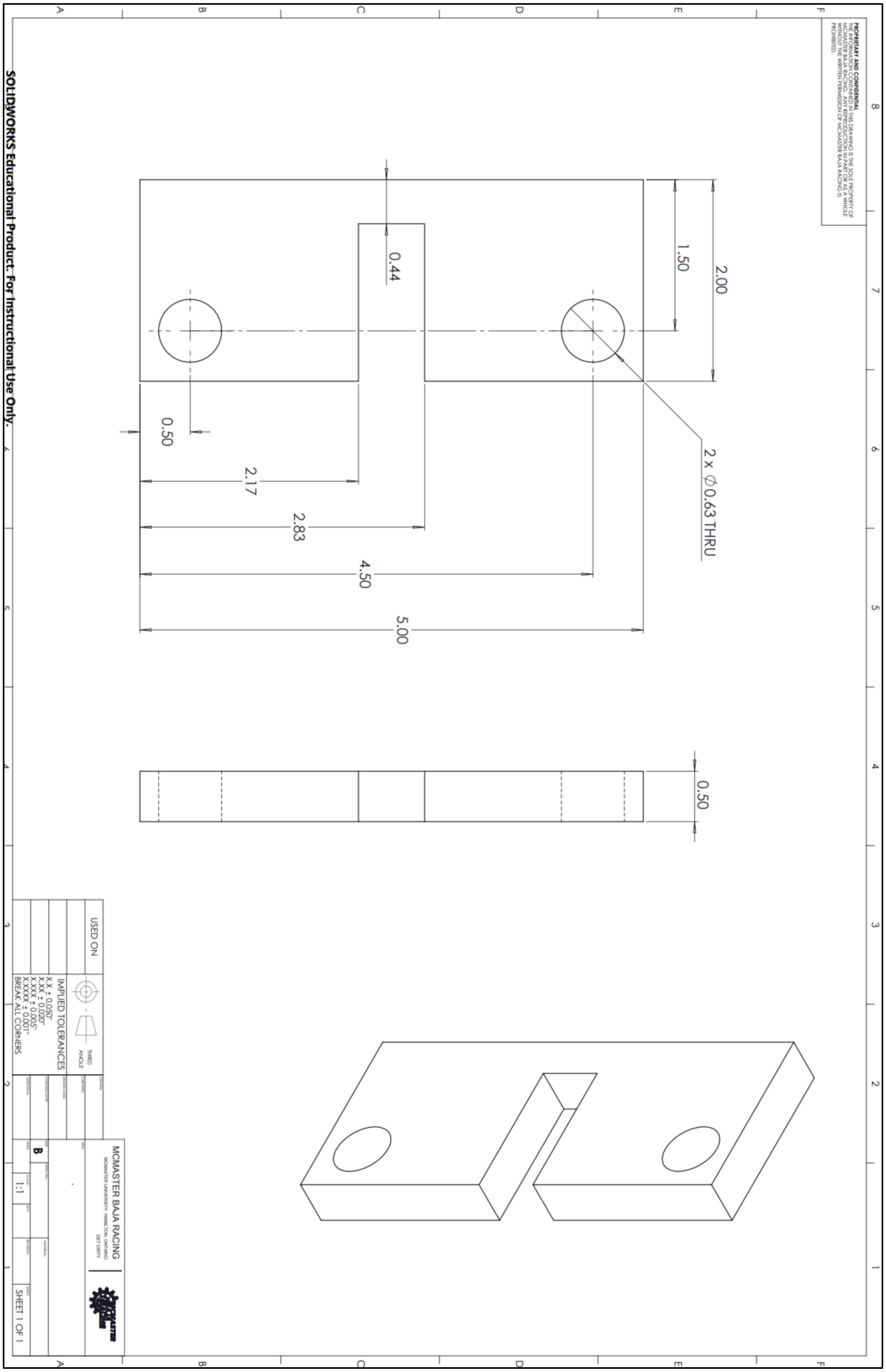


Figure 54:Drawing of Pulley Base.

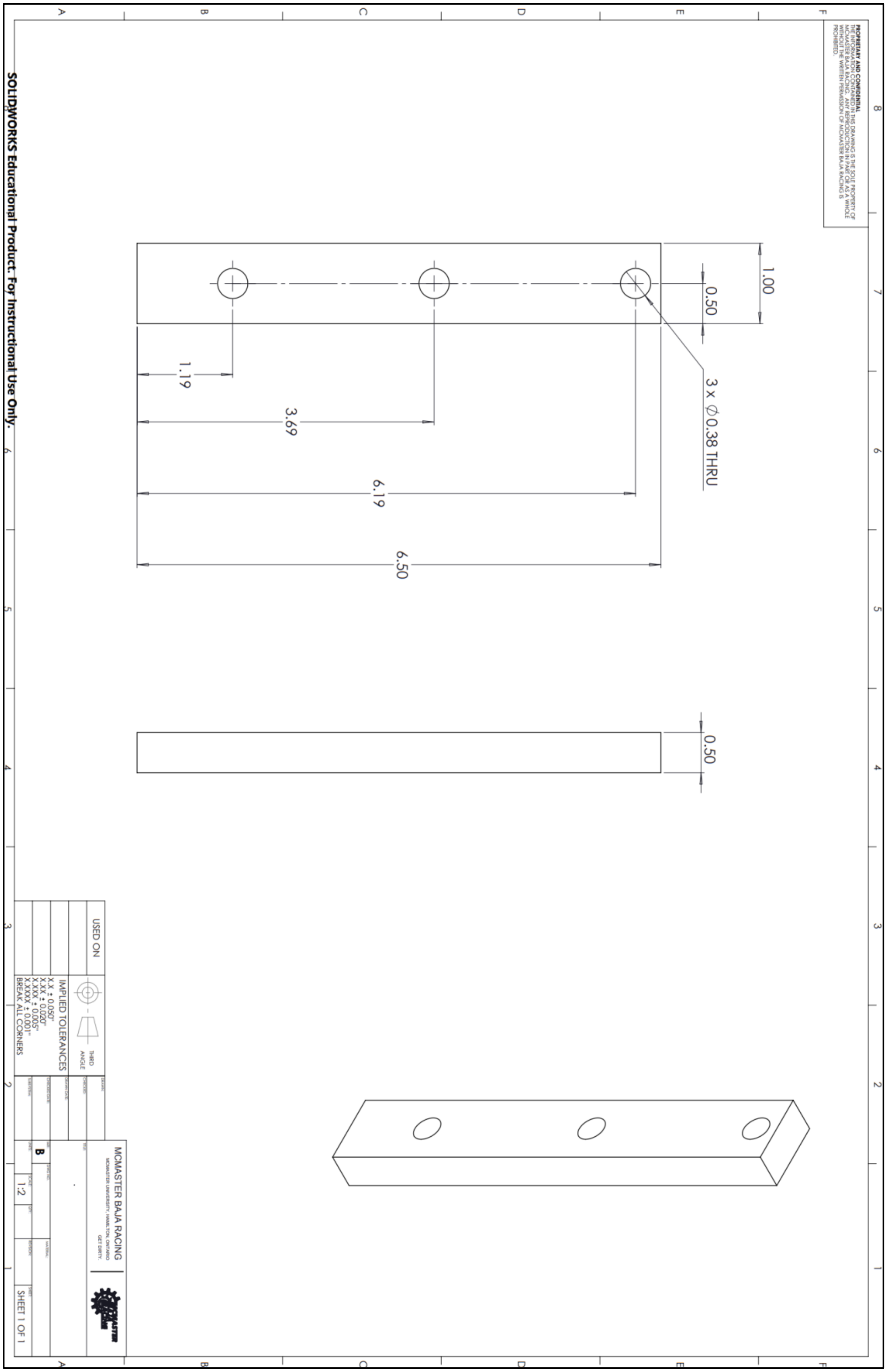


Figure 55: Drawing of Pulley Tower.

Appendix G – Purchase Order Form:

McMaster University | Department of Mechanical Engineering

Purchase Authorization Form 10-2019

Section 1: Account Information

Account Holder:	
Account #:	
Project Name:	MA02 (Baja SAE Wheel Force Transducer)

Section 2: Person Requesting Funds

Full Name:	[redacted]	Student/ Staff ID:	[redacted]
Email Address:	[redacted]	Telephone:	[redacted]
Affiliation:	☑ Undergraduate ☐ Grad Student/ Post Doc	☐ Staff ☐ Faculty	

Section 3: Purchase Information

Vendor:	Digikey Canada		
Contact Name:	N/A (online order of off-the-shelf components)	Telephone:	N/A

Description:
Include Part Numbers and Quantities if applicable and/or attach quotation
If the part is to be manufactured, include a sketch of the part below or attach drawings, note individual part cost on each sketch.

Part Number:	Qty:	Unit Price:	Total Price:
CH865-ND	3	$2.65	$7.95
1568-DEV-20359-ND	1	$44.51	$44.51
2254-M30X250H-ND	20	$0.269	$5.38
1568-KIT-20120-ND	1	$10.61	$10.61
931-1489-ND	2	$16.21	$32.42
1568-WRL-18569-ND	3	$2.79	$8.37
473-8800-375ML-ND	1	$122.20	$122.20

The website is:
www.digikey.ca

TOTAL COST:
CAD $ 261.53

Must Include:
☑ Tax ☐ Currency Conversion
☑ Shipping Cost ☐ Import Duties

Section 4: For Technician Use Only

Date Ordered:		Time:	
Contact:		Delivery Info:	

Section 5: Approval

Authorizing Signature (account holder)	[redacted]	Date:	2024-03-07

Figure 56: Purchase order form, including details of products purchased from Digi-Key through the capstone budget from the Mechanical Engineering Department.

Appendix H – Calibration Curves:

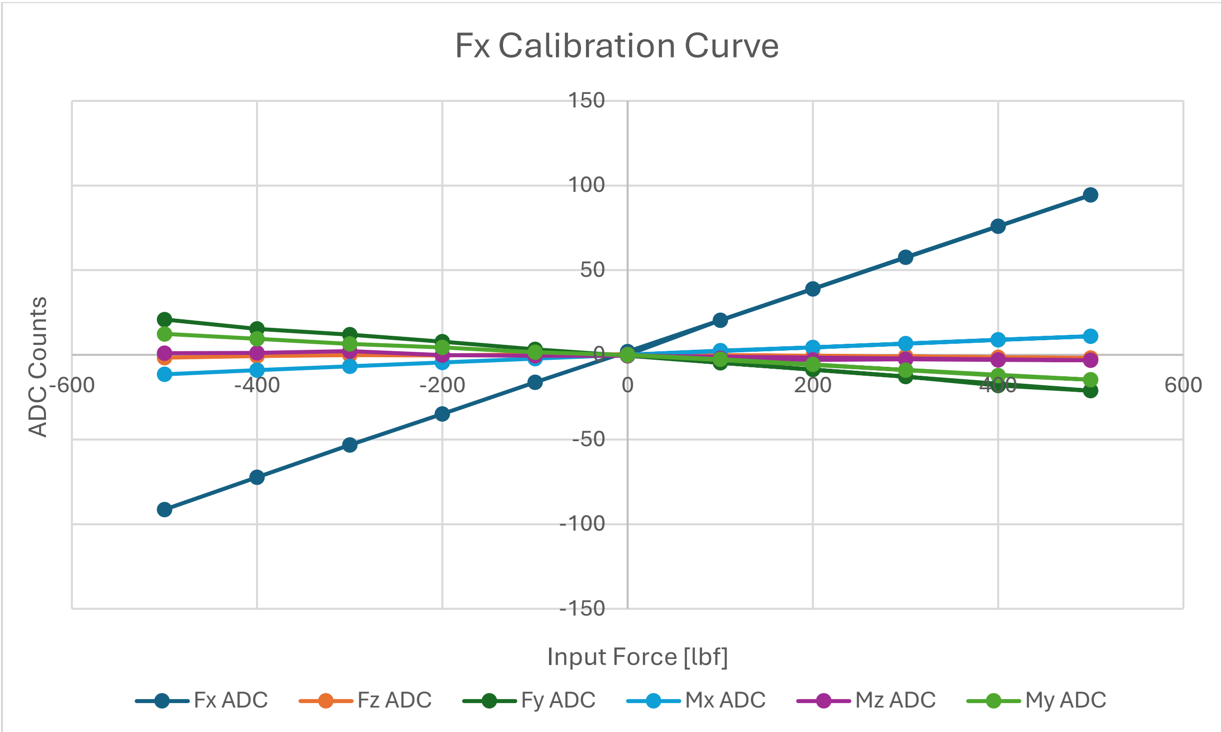


Figure 57: Calibration curve for X axis force data.

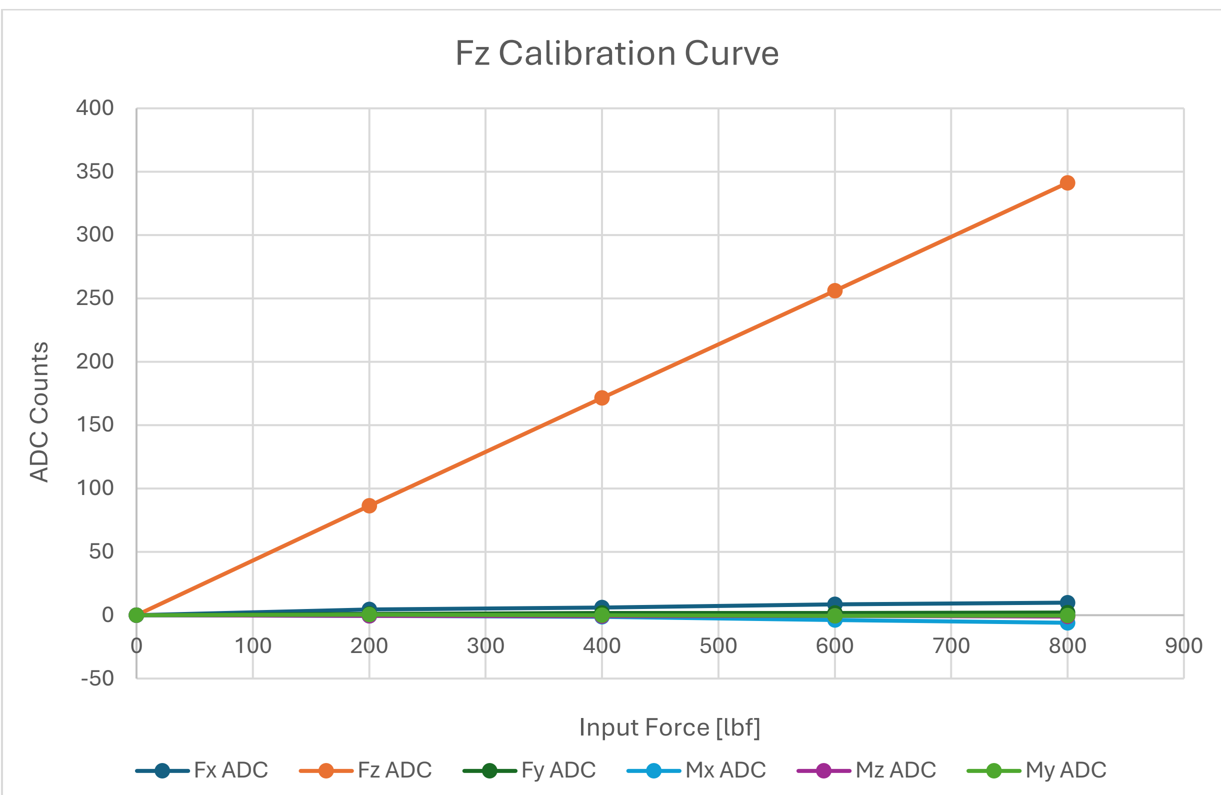


Figure 58: Calibration curve for Z axis force data.

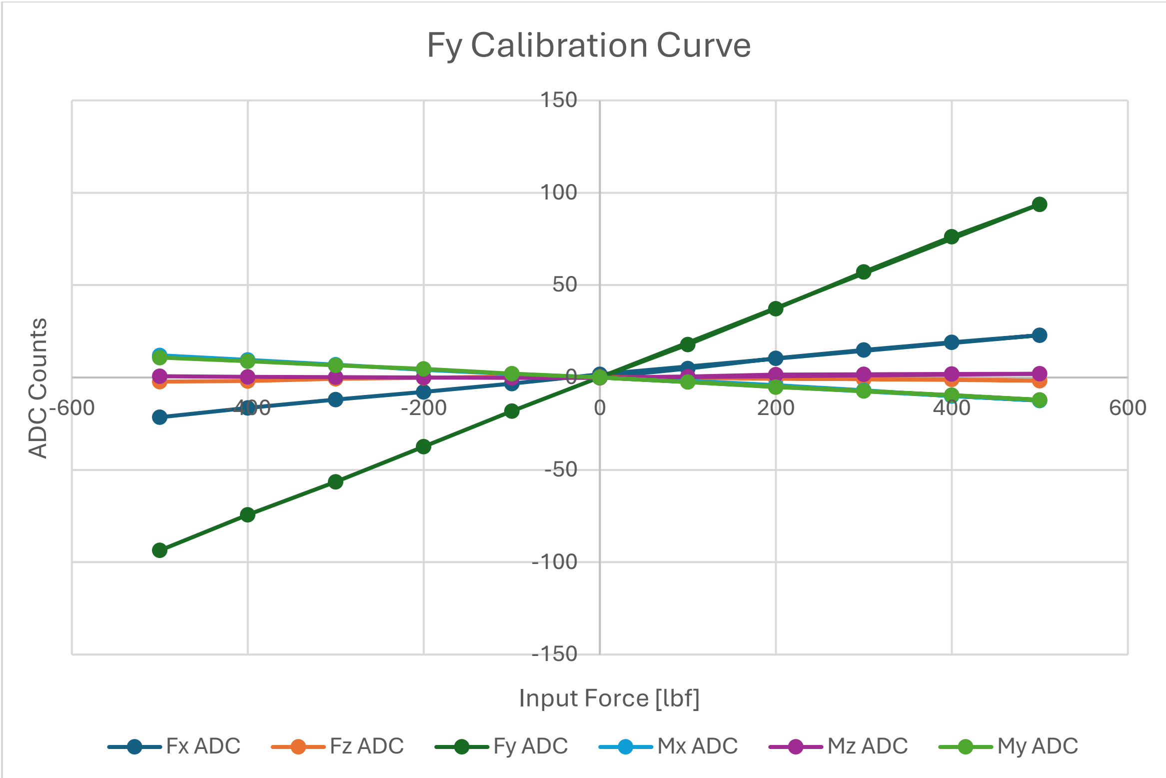


Figure 59: Calibration curve for Y axis force data.

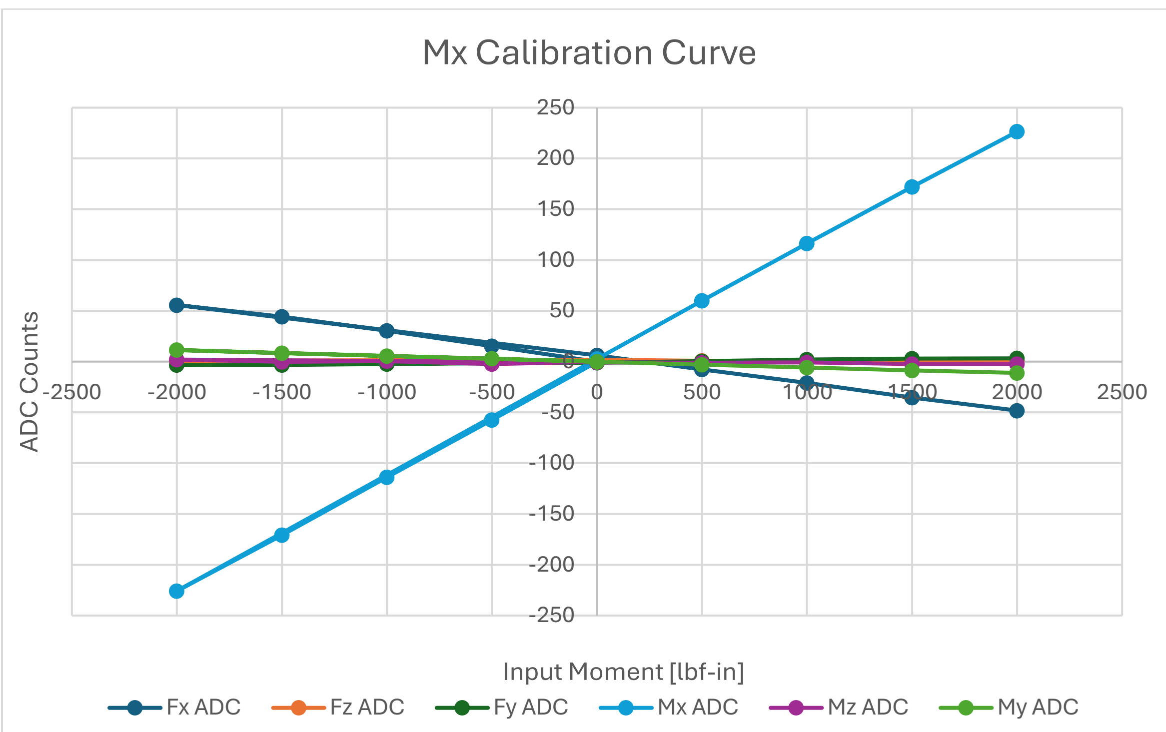


Figure 60: Calibration curve for X axis moment data.

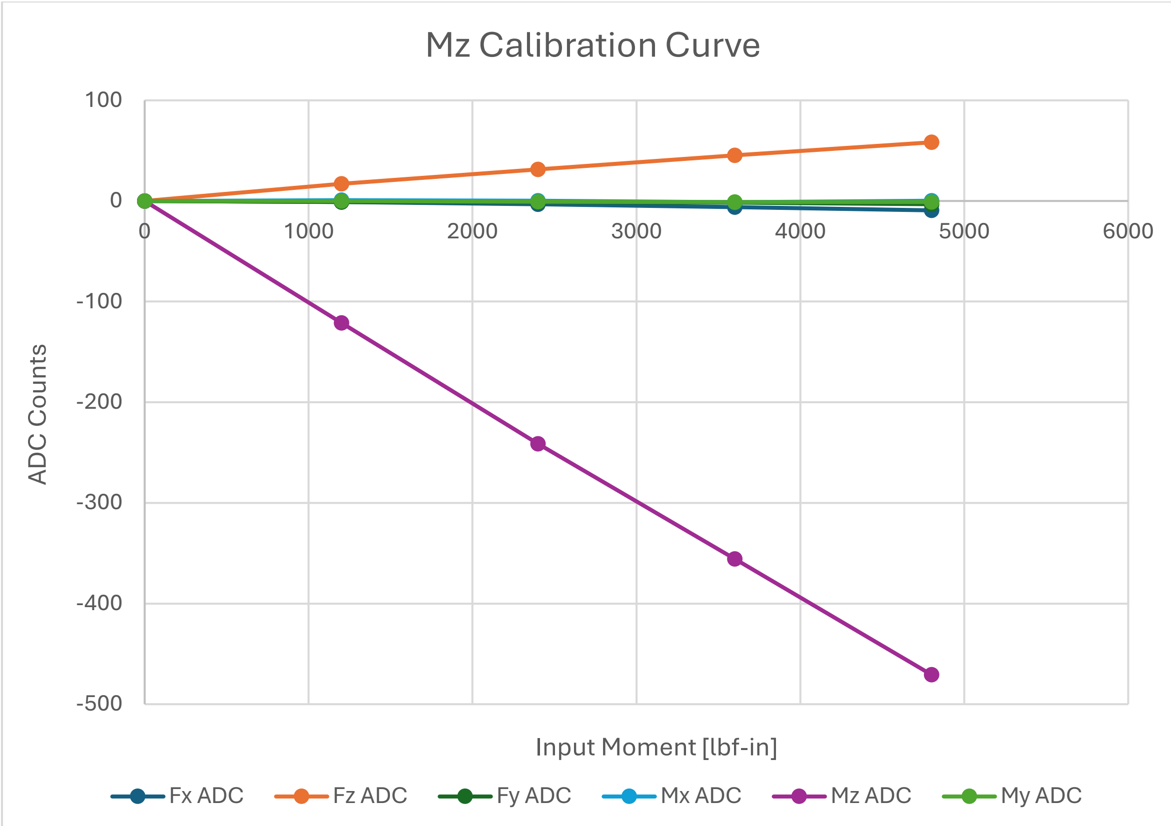


Figure 61: Calibration curve for Z axis moment data.

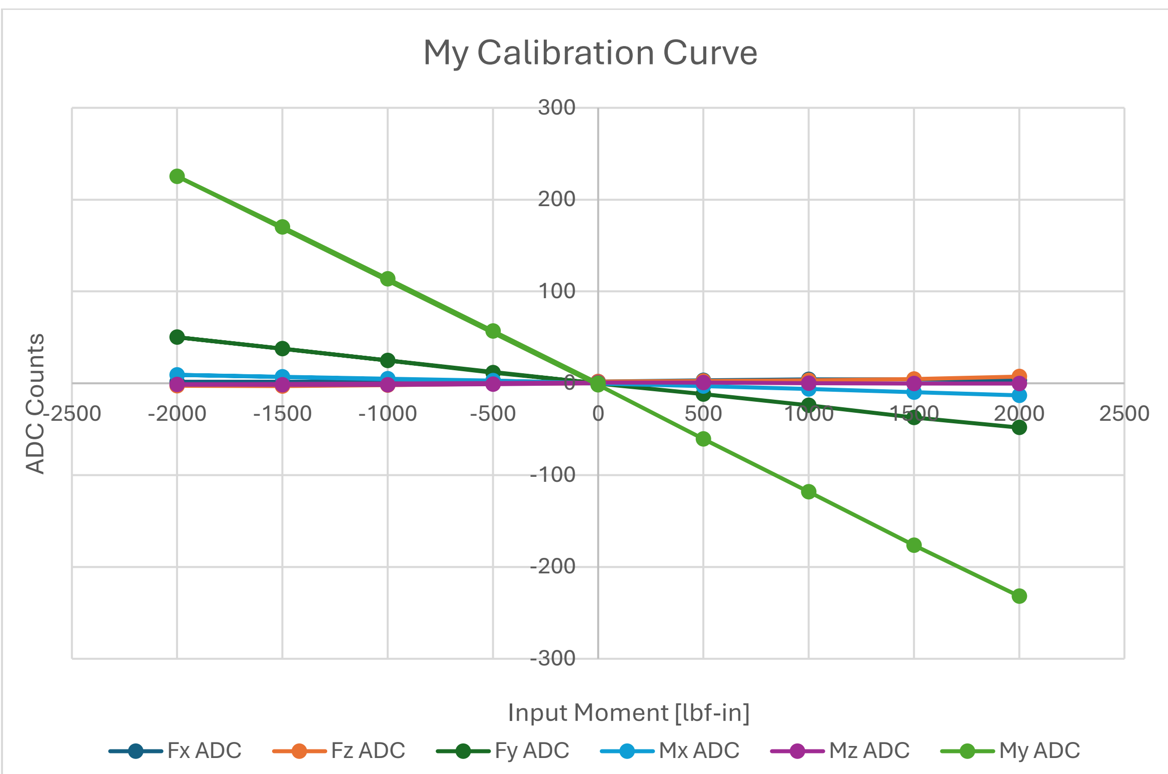


Figure 62: Calibration curve for Y axis moment data.

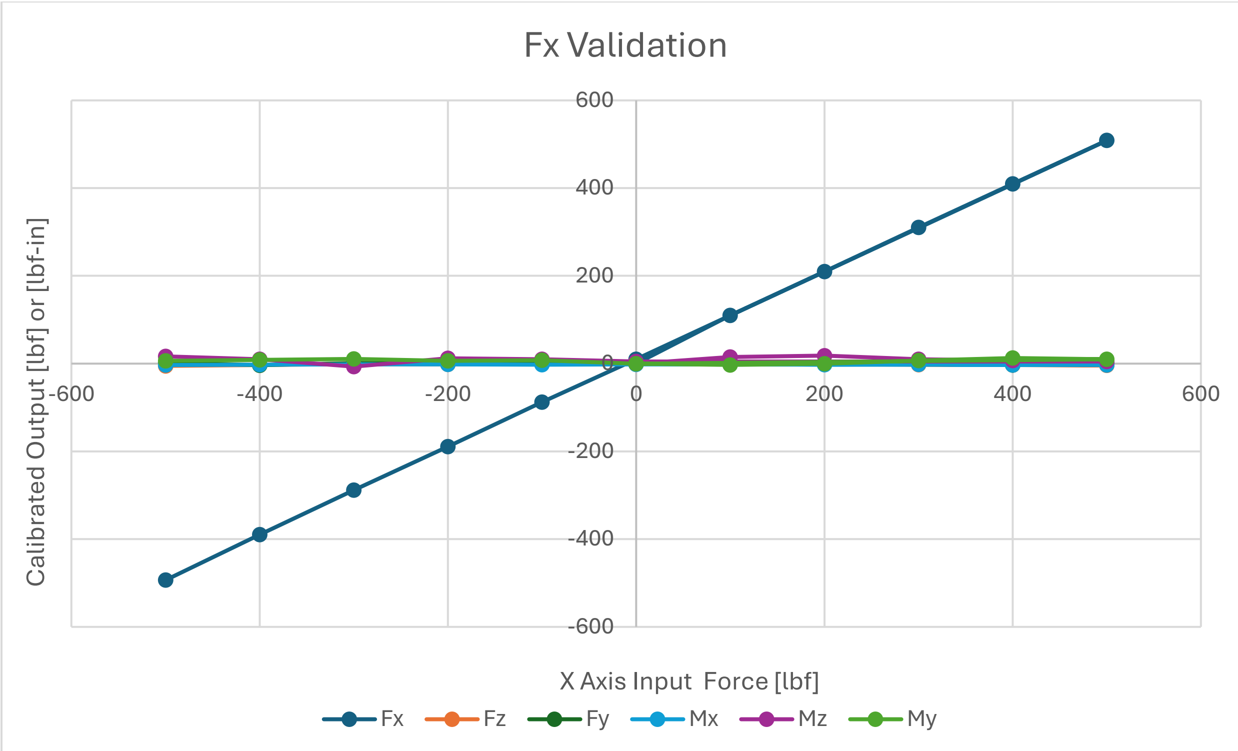


Figure 63: Validation plot for X axis force data.

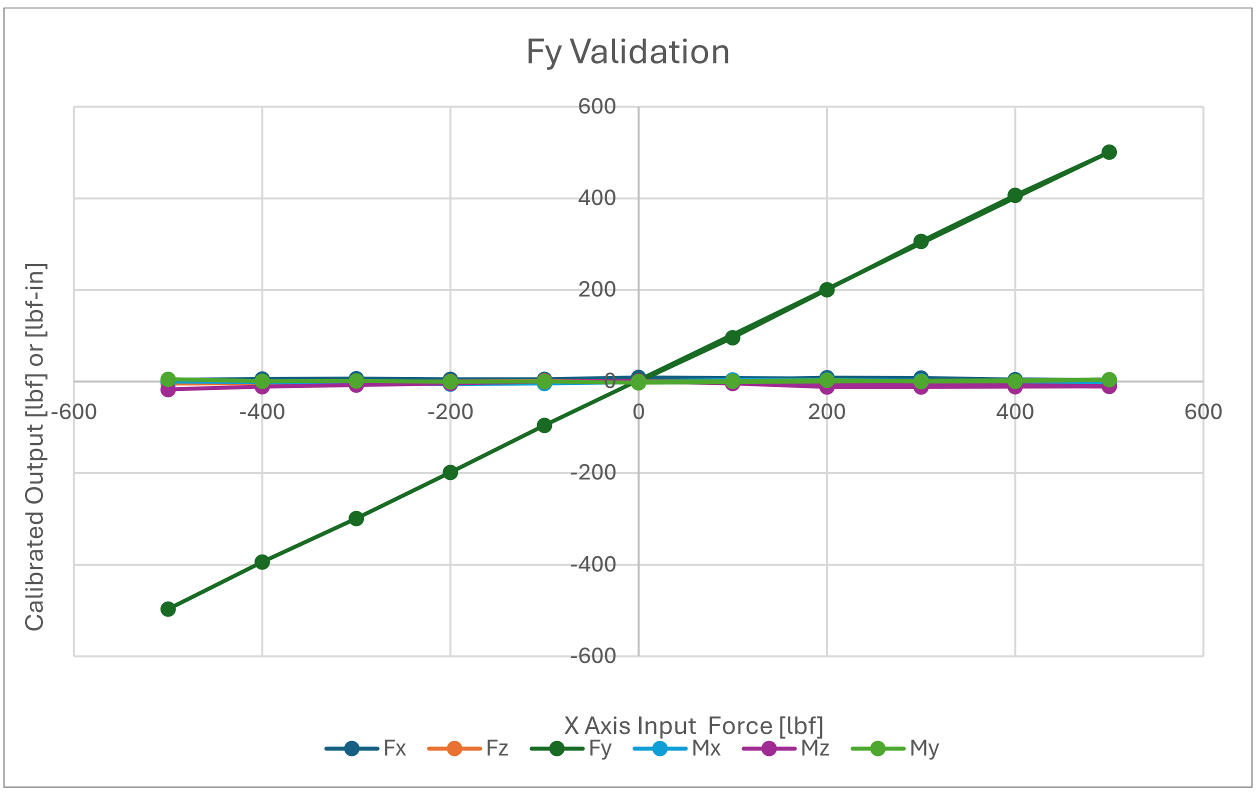


Figure 64: Validation plot for Y axis force data.

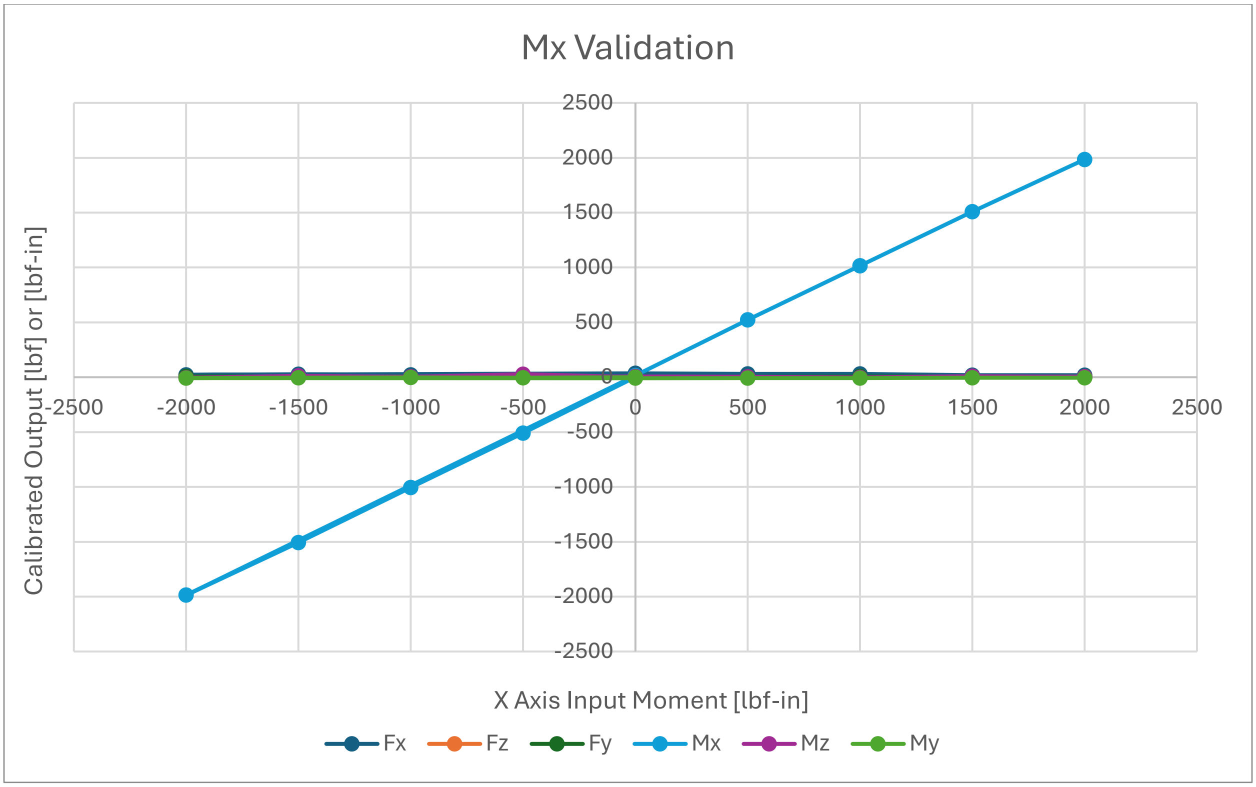


Figure 65: Validation plot for X axis moment data.

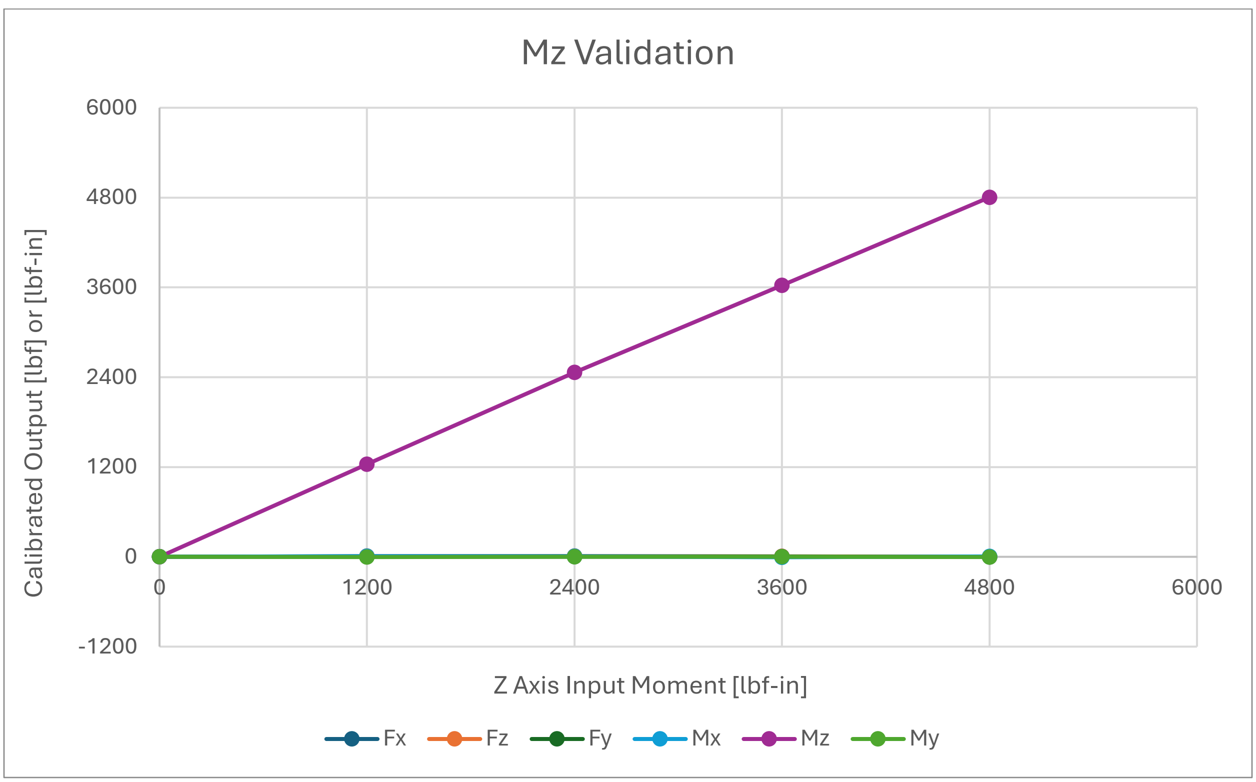


Figure 66: Validation plot for Z axis moment data.

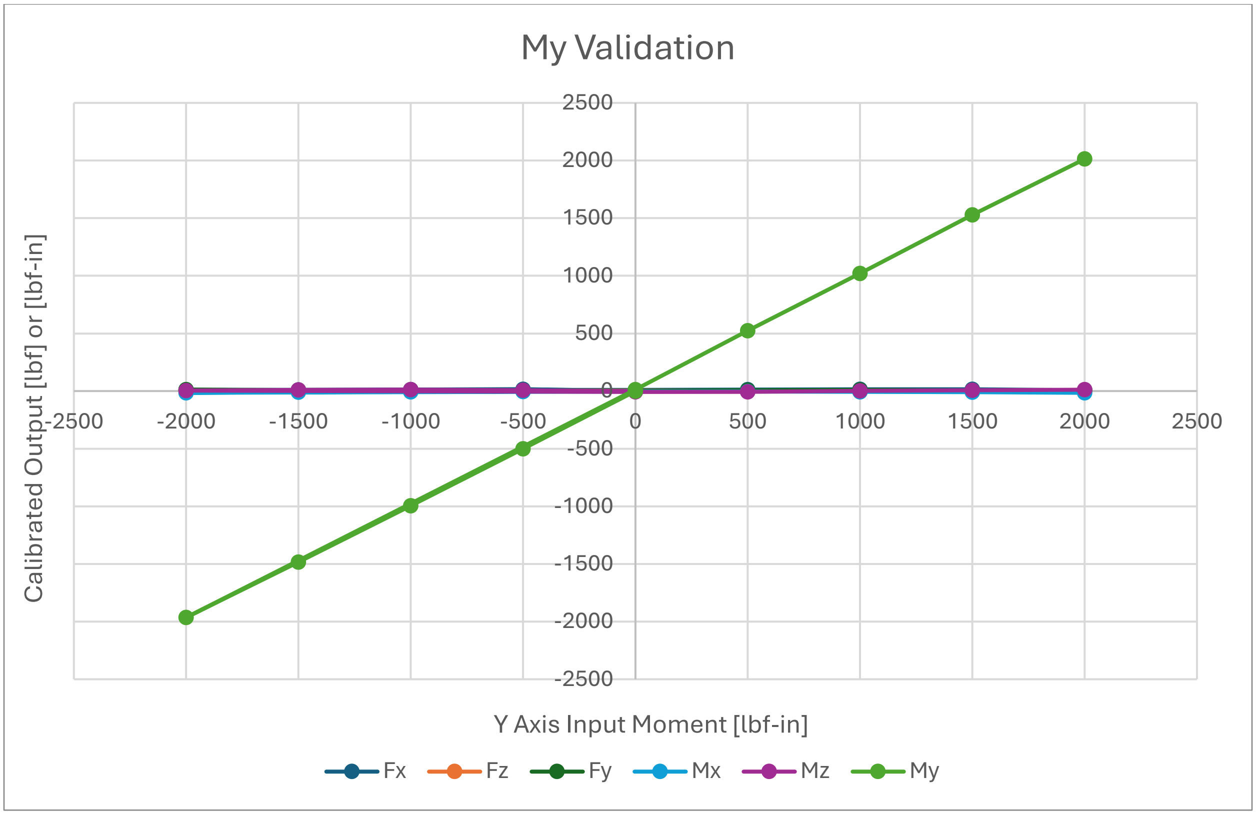


Figure 67: Validation plot for Y axis moment data.

Appendix I – Electrical Schematics:

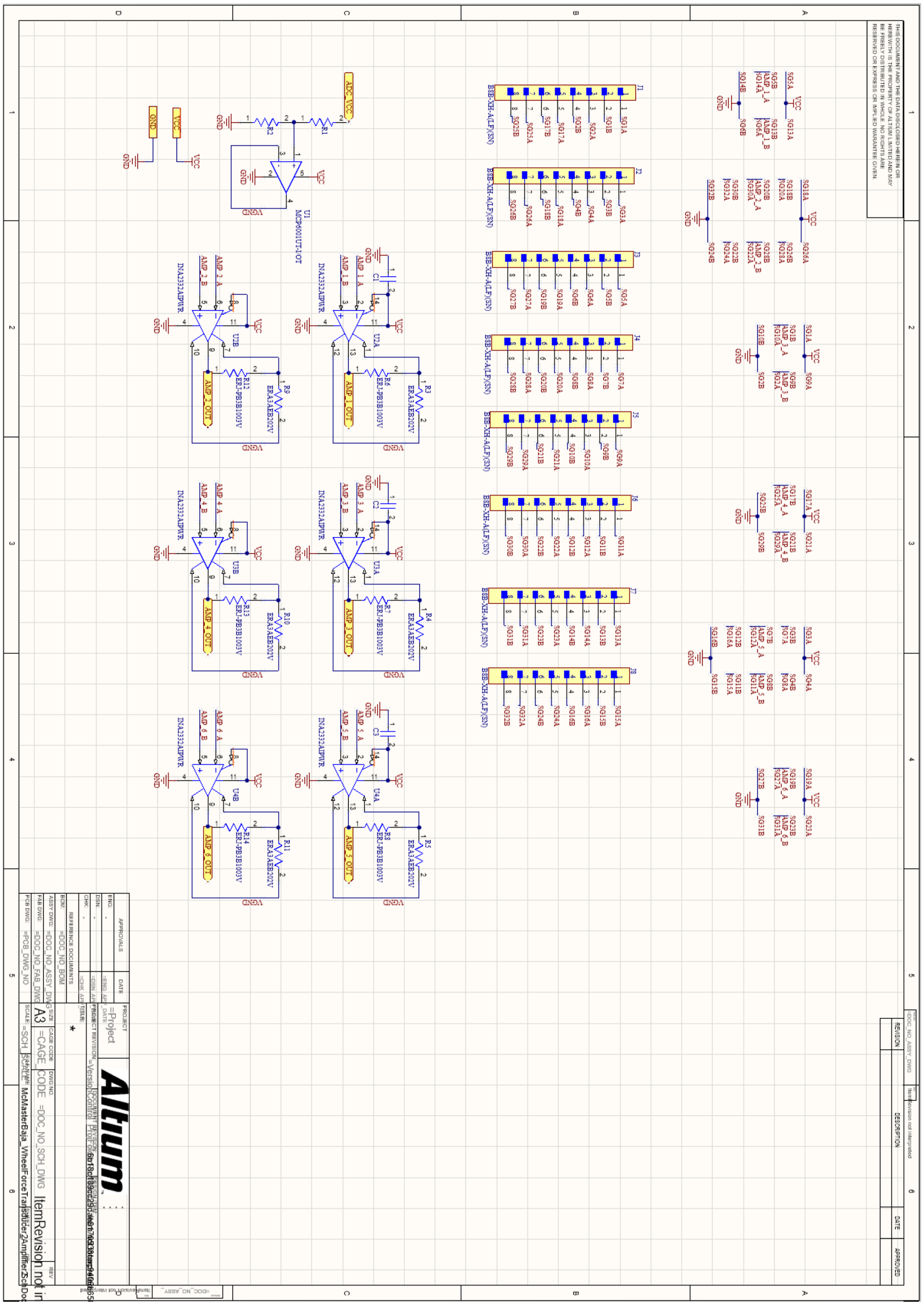


Figure 68:Bridge layout and amplification schematic.

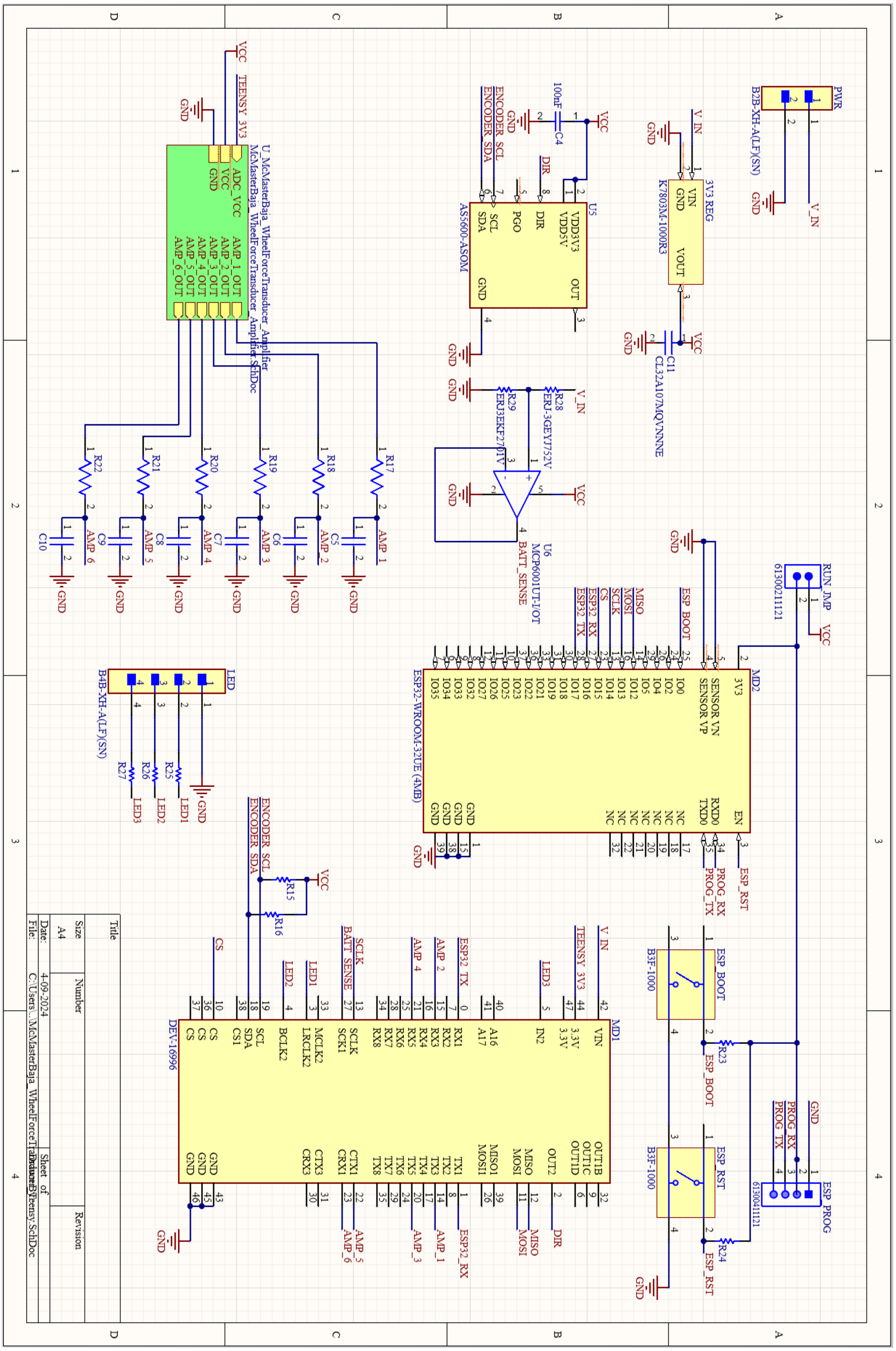


Figure 69:Microcontroller schematic