Autonomous Vehicle Test Dummy Mount

ME 450 Winter 2026 Team 16

Amogh Bollapalli, Peter Florence, Dale Newman, Andrew Spagnuolo

Instructed by Dr. Steven Skerlos

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Executive Summary
The purpose of this project was to redesign the autonomous vehicle dummy mounting system used with the UFOnano platform at Mcity/UMTRI. The existing mounting system presented issues due to its inconsistent retention and premature detachment which led to frequent resets and thus reduced experimental throughput. The inadequacy of this system reduced the testing efficiency of autonomous vehicle braking test operations. Therefore, the goal of this project was to deliver a mounting solution capable of securely holding the dummy during normal robot motion, detaching safely during vehicle impact, remaining overrunable, and allowing for fast one-person replacement in the field.

The team translated stakeholder needs into engineering specifications related to attachment strength, controlled detachment, remounting time, profile constraints, durability, and usability. These specifications guided the development of multiple concept categories, including magnetic retention, mechanical latch systems, tethered systems, and hybrid concepts. Our final design was selected because it provided an effective balance between secure attachment, predictable release, low-profile packaging, manufacturability, and operator usability.

The final prototype was fabricated and tested against the project's critical specifications. Verification testing at Mcity allowed the team to evaluate the prototype's retention under operational load conditions, detachment behavior, setup time, physical compatibility, and repeated use durability. The prototype successfully completed acceleration/deceleration verification testings, passing 20 out of 20 tests as intended. These results indicate that the prototype efficiently addresses the most crucial stakeholder needs, while also identifying opportunities for continued evaluation, particularly long-term durability and environmental exposure.

Overall, the team produced an evidence-based mounting solution that successfully improves reliability and efficiency of autonomous vehicle testing. It is recommended that future work focuses on extended cycle testing, winter-condition performance validation, and continued sponsor field trials to confirm consistent performance across a wider range of test scenarios.

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Abstract
This project aims to develop a quick-swap mounting system for pedestrian and cyclist targets used for emergency braking testing at Mcity. The current mount is unable to prevent consistent detachment before impact. The proposed design improves the magnetic retention by modifying the UFOnano to accommodate the secure placement of more magnets and tethers and enhancing detachment under vehicle collision. Engineering analysis, concept evaluation, and prototyping are being conducted to validate the system's ability to satisfy safety, durability, and operational requirements. The final deliverable will be a validated prototype providing reliable, repeated detachment under intended operating conditions in testing environments.

Project Intro, Background, and Information Sources
Vulnerable road user (pedestrians and cyclists) fatalities from vehicle accidents are increasing, reaching a value of 8,840 in 2023 [1][2]. To avoid this, and to protect both the driver and road users, advanced driver assistance systems (ADAS) features have been introduced. They provide emergency warnings and control, and one important feature is autonomic emergency braking (AEB). Cars in the US and Europe are not federally mandated to have AEB systems, but in 2029, the US government is mandating a new safety standard (FMVSS 127), requiring all US vehicles to have AEB [3].

Mcity is a 32 acre testing ground at the University of Michigan for autonomous vehicle research [4]. Mcity researchers are simulating autonomous emergency braking vehicle systems on a specific adult pedestrian dummy. Other organizations such as Euro NCAP, NHTSA, and IIHS also model emergency braking on pedestrian dummies, but use a robotic carrier to transport the dummy, since there is no notable alternative that can model complex pedestrian behavior.

The robotic carrier being used by Mcity is the UFOnano, shown below.

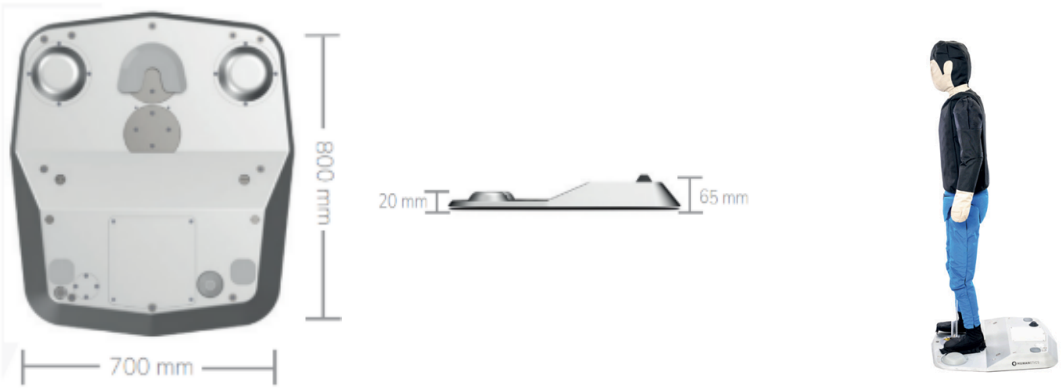


Figure 1. Visual representation of UFOnano

The UFOnano was created by Humanetics, the leading manufacturer in crash test robots. It was designed to test AEB safety for vulnerable road users. It has a 700mm by 800mm footprint, and a maximum height of 65mm, allowing it to be undetected by vehicle radars. It has a robust acceleration of $3m/s^2$ and has no turning radius, so it can simulate various pedestrian-vehicle impact scenarios such as straight line, turning, and lane changing [5][6]. AEB testing is almost entirely administered, innovated, and specified by Euro NCAP, a private organization that administers optional safety tests [7]. This is because AEB is not one of the currently mandated ADAS systems. Cars that perform well on this testing are given a safety rating out

of five stars. Euro NCAP's AEB testing is extremely stringent and their testing protocol directly follows the requirements specified in ISO 19206-2, 19206-4, and 19206-7. 19206-2 specifies the size, shape, and other physical properties for pedestrian targets and sensor requirements for detecting them [8]. 19206-4 specifies the same but for bicyclist targets [9]. 19206-7 specifies the testing methods for validating robotic target carriers and the testing procedure for performing vulnerable user road testing that is followed exactly by Euro NCAP and safety organizations [10]. In 2022, the UFOnano, which also directly complies with ISO 19206-7, was approved for Euro NCAP's official supplier bulletin (TB029) for AEB testing [11].

AB Dynamics and 4activeSystems innovated their own target carriers for this purpose. In 2021, the LaunchPad 80 [12] and FB target carriers (large, small, eco) [13] were introduced by AB Dynamics and 4active Systems, shown below respectively.



Figure 2. Representation of LaunchPad 80 (left) and FB eco (right) target carriers

AB Dynamics used a belt propulsion system to transport the carrier perpendicular to the vehicle path [14]. They used a steering robot and electric motor to power a belt, over which the carrier followed. A precise encoder was used to measure the position of the belt. The belt tension was monitored and if it suddenly changed, the motor was stopped. An image of the system is shown below.



Figure 3. Representation of belt propulsion system used by AB Dynamics

While this was also approved in TB029 and used for some Euro NCAP tests, it was not able to model complex pedestrian movement due to having one degree of motion. Having a robot carrier that can independently move was significantly more effective for AEB testing. Because of this, robotic carriers have been the gold standard in research for performing vulnerable user AEB testing.

To run these tests, Mcity mounts the dummy to the UFOnano and transports it into the correct position. The test is performed, and if the car does not brake in time, it hits the pedestrian. During impact, the pedestrian-robot mounting interface needs to detach completely so no damage is dealt to the vehicle, mount, robot, or dummy. The current mounting design involves a magnet in the center of the robot that

secures the pedestrian dummy, with a tether through the top of the dummy that mounts in the front and back of the robot to provide increased stiffness, shown below.

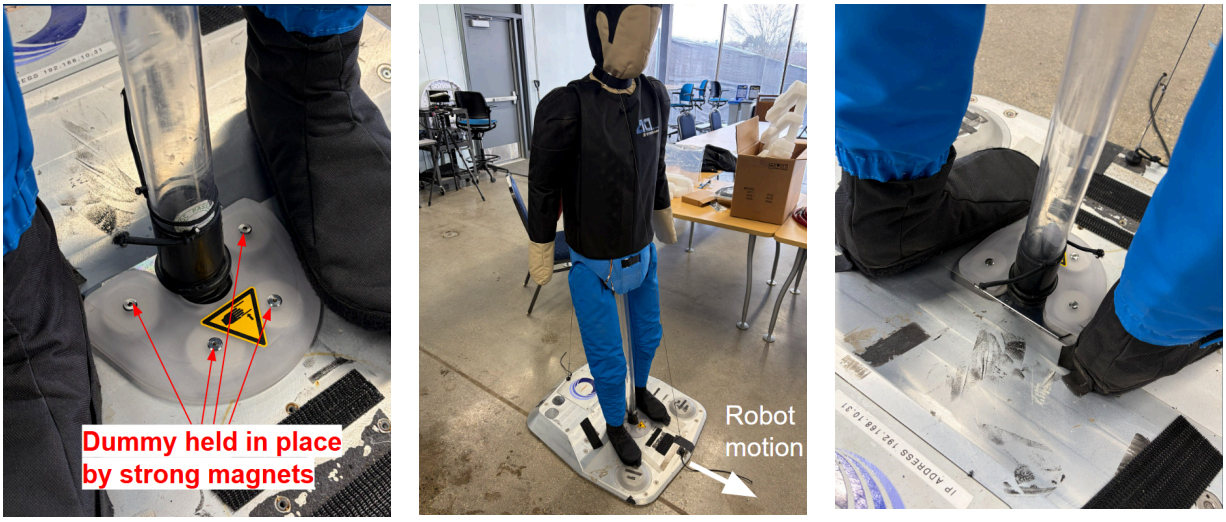


Figure 4. Representation of magnetic mounting mechanism

However, Mcity is noticing that when the robot experiences a rapid change of acceleration, the tethers unhinge from the robot and the dummy falls off. This requires remounting of the dummy and lowers the productivity of testing. To fix this, Mcity is requesting a new mount design that does not detach when the robot rapidly changes acceleration, but also is compliant enough to allow separation during impact without causing damage to the vehicle or mount. They also want this to be ensured during all testing conditions, such as wind, snow, and ice. Solving this problem will significantly improve Mcity's AEB test output per day and advance vulnerable user and driver safety.

Design Process

Since Design Review 1, the team's design process has shifted from its primarily planned iterative, requirements-driven process to a more actively implemented, experiment-driven cycle informed by early concept exploration and analysis. We initially proposed this framework due to an uncertainty in loading conditions and performance constraints. However, as the project evolved, we developed the understanding that the uncertainty is greater than initially anticipated, therefore supporting the need for flexibility and continuous refinement.

Previously, our team aimed to develop our requirements prior to engaging in extensive concept development. The process was shifted, however, after early investigation allowed us to determine that the forces required for reliable retention and controlled detachment could not be defined accurately without empirical data. Therefore, we decided our design process would benefit from incorporating earlier experimentation and benchmarking in our specification development rather than treating our previously existing specifications as fixed inputs.

Our concept generation phase further influenced the evolution of our process. Through the use of structured ideation sessions, clustering, rapid sketching, and design heuristics, the team was able to develop a wide range of fundamentally different approaches. In order to evaluate these concepts

objectively, we incorporated formal selection methods such as weighted screening and Failure Modes and Effects Analysis (FMEA).

Our current process emphasizes continuous feedback between requirements, concepts, analysis, prototyping, and testing. This is crucial because the mounting system is characterized by the "Goldilocks" problem described initially where the retention force must be high enough to prevent unintended detachment during normal motion, but low enough to ensure reliable intended release. Therefore, in order to converge on an acceptable force window, empirical testing is needed.

Compared to the initial design process described in DR1, our process now prioritizes the iterative refinement of specifications as well as validation through analysis and experimentation. It is also crucial to incorporate stakeholder input and testing results in the guiding of future design iterations. This evolving process enhances the development of a solution that effectively meets performance, safety, durability, and usability requirements, while mitigating the likelihood of late-stage redesign.

Design Context

Our major stakeholders are Humanetics, the manufacturer of the robot; UMTRI research teams who use the robot for automated vehicle testing; AV manufacturers; NHTSA and other transportation research partners; and pedestrians and the general public who indirectly benefit from improved safety validation. These stakeholders will be positively impacted by our product due to the increased safety testing efficiency. The current mounting system is not only inefficient but also has the potential to be dangerous, as premature detachment can lead to vehicle damage, corrupted test data, and operator injury, so improving the safety of the testing process is critical in our design in addition to improving efficiency.

The broader social motivation for this project is to support the safe deployment of AVs. This is done by more efficient and repeatable tests. While our mount changes will not directly improve public safety, it will contribute to the research infrastructure that produces higher quality AV safety data. Our sponsor prioritizes durability and robustness over profit and commercialization, which is evident due to there not being a goal of mass production or patent protection.

Intellectual property has not played a role in the project thus far, as the design is intended for internal research use only. Sustainability considerations surround potential impacts our design could have on other people and the planet. As we are operating in Michigan, corrosion due to moisture or salt is likely, so researching corrosion resistant materials or coating is a worthwhile endeavor. Positive sustainable impacts include a long service life and potential for repair instead of replacement, which is significantly cheaper than buying from Humanetics directly. Once the product reaches the end of its life, recycling or repurposing would be ideal, and our current solution is composed of magnets that are reusable or recyclable. Ethical considerations are focused on researcher safety and data integrity, which is addressed through conservative design, testing, and clear communication between all groups involved.

As our project has evolved, the team has developed a better understanding of the broader societal implications posed by the mounting system. In our quest to improve the accuracy of pedestrian scenarios, our solution has long-term impacts on autonomous vehicle technology, ultimately supporting safer transportation. The capability of our mount to improve vehicle-pedestrian safety evaluations ubiquitously enforces the need for a consistent, reliable mechanism with high functionality in real-world conditions.

Additionally, the mount's usability has a significant impact on the workload and safety of the personnel that will be operating the equipment. By prioritizing a system that effectively limits physical strain, minimizes downtime, mitigates risks to test vehicles, and improves experimental throughput, our mount can have a substantial impact on the effectiveness of vehicle testing operations.

User Requirements and Engineering Specifications

We have identified several user requirements through thorough review of relevant literature, stakeholder interviews, and hands-on testing of the current mounting system. These are listed in the table below and elaborated on after.

USER REQUIREMENT	ENGINEERING SPECIFICATION	TESTING and VERIFICATION METHOD
DUR - Durable	**DUR-01** Mount must withstand 1000+ cycles	**DUR-01-V** Run 100 cycles with double the force from detachment and inspect for cracking, permanent deformation, and loosening. Pass if none apply
PERM - Permissibility	**PERM-01** Under no circumstance void the warranty or applicable insurance policy	**PERM-01-V** If any changes are made to the robot, contact both humanetics and the insurance company. Pass if given written approval for changes.
SIM - Simple	**SIM-01** Only takes 1 person to remount	**SIM-01-V** Have 1 person perform remount for 3 trials. Pass if completed correctly without assistance.
	SIM-02 No tools necessary	**SIM-02-V** Attempt full remount using only hands. Pass if can be done for 3 trials.
	SIM-03 Can be done in under 2 minutes	**SIM-03-V** Time from the initial movement of the dummy to full remount, 3 times. Pass if all trials are under 2 minutes.
REL - Reliable	**REL-01** Remains attached to the UFOnano 95% of the time when accelerating at 3 m/s^2 longitudinally	**REL-01-V** Run the UFOnano through 20 acceleration tests at 3 m/s^2. Pass if no detachment for 19 of the tests.
	REL-02 Remains attached to the UFOnano 95% of the time when accelerating at 1.5 m/s^2 horizontally	**REL-02-V** Run the UFOnano through 20 deceleration tests at 1.5 m/s^2. Pass if no detachment for 19 of the tests.
	REL-03 Remains attached 95% of the time in environments with wind speeds up to 5 m/s per NCAP standards	**REL-03-V** Use a calibrated anemometer to measure wind speed above 5 m/s, and run 20 tests into the wind speed. Pass if there is no detachment for all 19 tests.

IC - Impact Conditions	**IC-01** Pedestrian dummy must be released from mount after experiencing 100 N in Y direction at 2.5 feet off the ground	**IC-01-V** Attach scale to dummy 2.5 feet off the ground and measure force to detect dummy from the robot, and pull in the Y direction. Pass if scale reads over 100 N for 3 consecutive attempts.
	IC-02 Pedestrian dummy must be released from mount after experienced 100 N in X direction at 2.5 feet off the ground	**IC-02-V** Attach scale to dummy 2.5 feet off the ground and measure force to detect dummy from the robot, and pull in the X direction. Pass if scale reads over 100 N for 3 consecutive attempts.
COS - Cheap	**COS-01** Entire mounting system costs less than $300	**COS-01-V** Bill of materials with links, quantities, and shipping/tax included. Pass if total is under $300
	COS-02 Replacement common failure parts must cost less than $25	**COS-02-V** Identify "common failure parts" and list replacement cost. Pass if each part is under $25
OVBL - Overrunnable	**OVBL-01** All physical parts on the front must remain within the 20mm-65mm profile	**OVBL-01-V** Measure front profile using calipers from the base plate as reference place. Pass if within the maximum allowed profile.
	OVBL-02 All physical parts on the rear must remain within the maximum height of the antennas	**OVBL-02-V** Measure maximum rear height of the antennas, and measure the maximum height of the rear components added, with the base plate as reference for both. Pass if the height of the antennas is greater than the components added.
	OVBL-03 Dummy must detach from robot upon impact with vehicle	**OVBL-03-V** Initially knock over the dummy by hand to ensure release, followed by slow speed testing by vehicle. Pass if dummy detaches during both tests.
	OVBL-04 Physical parts should not be able to be damaged by or cause damage to testing vehicle	**OVBL-04-V** Test on Mcity truck that can sustain damage, and perform inspections, with photographs, before and after 10 simulations. Pass if no visible damage occurred after all tests.

RLST - Realistic	**RLST-01** Fulfills the temperature, wind speed, and accuracy of carrier standards specified in ISO 19206-7 for NCAP testing.	**RLST-04-V** Ensure testing conditions have an ambient temperature between 0 and 30°C with a wind speed under 5 m/s. Accelerate target carrier at test speed. Stabilize and record speed, lateral deviation, yaw. Repeat this again. Tolerances given are within 0.2 kph for speed, 0.05m for lateral deviation, and 1 deg/sec yaw. For each parameter fill in a table: minimum, maximum, and average for each of the two runs. Then calculate the percentage of the time these variables are in the tolerance. Pass if the worst % time among both runs is at least 85%.

The first user requirement we identified is that our design must be durable. This was stressed heavily in our initial stakeholder interview. We spoke with Alex Rozelle, one of the operators of the UFOnano at Mcity, and he emphasized that being able to withstand many mounting cycles is critical [16]. We set the baseline specification at at least 1,000 cycles, but ideally it will withstand more. Another critically important requirement Alex emphasized is permissibility. Any alterations we make to the UFOnano robot cannot, under any circumstances, void any applicable warranty or insurance policy. Alex said the likelihood of any of our concepts or proposed alterations being impermissible was low as the insurance policy is of a research and educational nature, so the scope of the policy is quite large. The mounting system we design must be simple. The mounted dummy comes off the robot with regularity, so performing a complex mounting sequence would significantly hinder the tests. We have specified that the mounting sequence should be completable by one person, with no tools, in two minutes or less.

The main problem that Alex described to us was premature detachment as a result of sudden acceleration. Every time this happens the test is immediately stalled and Alex has to remount the dummy. We need to design a solution that is reliable, where it stays on the robot when desired and falls off the robot when desired. This leads into our next requirement, which is detachability. The dummy has to fall off the robot when struck with the vehicle. Any failure to detach could result in damage to the dummy, to the robot, to the vehicle, and to the operator. We will perform tests using a force gauge to measure the force required to detach the robot. One of the most important requirements that we have is that the mounting system must be overrunnable. No physical part of our system can protrude from the robot's profile, which means we have 45 mm of vertical space to work with. Our system must also not be damaged as a result of being run over, as well as it must not damage the vehicle.

Problem Domain Analysis and Anticipated Challenges

The final deliverables for this project will be the fully functional prototype mounting system for configuring pedestrian and cyclist targets to the UFOnano. The prototype will effectively meet all design requirements, specifically reliable retention during acceleration/deceleration, controlled detachment under intended conditions, durability after repeated use, and compatibility with existing UFONano hardware. In

addition to the physical prototype, we also intend to provide supporting documentation, such as the CAD models, engineering analysis, test results, and validation procedures.

The deliverable can be both prototyped and validated within the remaining half-semester. Manufacturing of the mount components is feasible using provided machining, and performance under repeated cycles can be evaluated through laboratory testing and field trials at Mcity. In order to ensure efficient reiterations, testing methods such as force application and dynamic loading assessments will be used to approximate real-world conditions prior to continuing with vehicle impact testing. The use of these testing methods will also provide conservative estimates of system performance should logistical constraints complicate our ability to perform full-scale impact testing at Mcity.

The primary drivers of the design are the retention force characteristics, geometrical constraints imposed by the UFOnano structure, and durability in real-world conditions. Achieving a precise balance between sufficient attachment strength and reliable release is the central technical challenge of our project. Other factors that prove highly influential to our design decisions include our overrunnability and ease of remounting requirements. In addition, the elevated center of mass of the testing dummy utilized causes additional moments to be applied, further increasing the complexity of the force behavior at the mounting interface. It is important to note that these interacting constraints imply the need for careful tradeoffs that avoid improving the performance of one feature at the risk of negatively impacting another.

The most significant anticipated challenge is our uncertainty involving the inertial forces during UFONano acceleration and the magnitude and direction of forces during impact. In addition, the impact of environmental conditions (moisture, debris, temperature) on the magnetic performance and material behavior must be evaluated for an accurate conclusion to be made on our prototype's effectiveness. These problems will be addressed through the implementation of iterative testing, conservative design margins, and adjustable design features allowing us to continuously tune retention strength. The use of an adjustable design allows the team to take efficient, corrective actions in response to unfavorable test results without the need for a complete redesign.

In order to successfully tackle problems, access to specialized equipment and expertise will be essential. We have already begun to use measurement tools, such as force gauges, to characterize detachment forces. More specialized measurements can be taken to narrow the range of our uncertainty regarding forces under different conditions. In addition, resources such as the ME Undergraduate Machine Shop will be used to manufacture the mount components. Access to field testing and personnel at Mcity will prove useful in accurately evaluating retention performance as well as the remounting process. Expertise in material selection, structural analysis, and magnetic systems will also be consulted as needed. Regular engagement with stakeholders will also assist in ensuring that emerging issues are promptly addressed and that the design remains aligned with operational requirements.

The existence of current information gaps, specifically the exact forces acting upon the mount during robot acceleration and vehicle impact, can be addressed through experimental testing, analysis based on known parameters, stakeholder engagement, and review of relevant standards. By actually analyzing the performance of the UFONano-Target interface during the operating conditions that the problems were initially observed in, we can develop a much more accurate understanding of the changes that must be

implemented in the final solution to address such problems. As we collect data from these situations, the refinement of specifications and design parameters will ensure the final prototype performs reliably in real-world contexts.

Concept Generation

Upon completion of a rigorous problem definition process and development of thorough user requirements and engineering specifications, we started the concept generation process. This process entails employing various verified and validated concept generation techniques to amass as many concepts as possible. Good concept generation involves quickly generating a large quantity of diverse ideas, and deferring judgement on the ideas until later. The vast majority of our concept generation was done in class during the concept generation session led by Professor Skerlos. [26]

The first concept generation method we used was an idea "purge" of sorts. We worked independently to come up with as many ideas as we could, and wrote each one on a sticky note. There was an emphasis on production as opposed to evaluation in this stage, as any evaluation can shrink the solution space. Once we purged for five minutes, we came back together as a team and sorted all the ideas into groups, or clusters. The clusters we ended up with were magnets, tethers, springs, latches, exotic magnets, and miscellaneous. The magnet cluster contained ideas like adding more magnets, making the magnets stronger, and changing the location and geometric orientation of the magnets. The tether cluster had ideas like changing the tether material, adding more tethers, and adjusting tether positions. The spring cluster involved ideas with integrating springs into the existing system, as well as removing the existing magnets entirely and having an entirely spring based mounting system. The latch cluster had ideas relating to more rigid mechanical securement, like an actuating clamp, latch, or disposable shear pin. The exotic magnet cluster contained our more novel ideas relating to magnets, like using electromagnets or quantum levitation. Our final cluster was the miscellaneous cluster, where we placed our stand alone ideas, such as using a jetpack or making the dummy itself walk, eliminating the UFOnano entirely. Once we had clustered our ideas, we observed where any gaps were, as well as any "overweight" categories, or clusters that were especially populated. We also noted any bridges between clusters that existed. For example, some of our ideas involved both magnets and tethers, or both springs and latches, or springs and magnets, to name a few.

Our next concept generation strategy was rapid sketching, or "Crazy 8s". We were given eight minutes, and we drew one sketch per minute for eight minutes. These sketches were to be "meaningfully different" and include a caption describing its general idea or purpose. After the eight minutes were up, we each chose two sketches to share, and selected one of the eight shared to iterate on. We worked together to generate improvements and variations on the selected idea, and documented those new sketches. The idea we iterated on was Drew's "splitter" idea, where we have a part that goes in an existing hole in the baseplate and has two ports for magnets, effectively splitting the hole into two. One idea that we came up with together was to manufacture the part to tilt slightly toward the robot. This would cause the magnetic attraction to be in line with the tether, strengthening the securement force.

We also used some of Professor Daly's Design Heuristics [27][28] to generate ideas. For example, Card 65 is "Telescope". This led to the idea to have a telescoping post that the dummy is attached to, as opposed to the rigid pole that exists currently. The post would telescope down at the right time, allowing

the dummy to be knocked off the robot by the car. Card 70 is “Use a different energy source”. This led us down a road toward electromagnetics, where the magnet could be turned off at the right time, allowing for detachment.

Concept Selection

Having generated our concepts, we wanted to evaluate their ability to meet our improved specifications. We initially created questions based on requirements we deemed absolutely necessary, calling these “must have” questions. Our most important design considerations were not severely modifying the internal robot design (voiding the warranty), having the dummy detach upon vehicle impact, fulfilling NCAP testing (refer to requirements and specifications chart), and having the dummy attached to the mount 95% of the time at maximum acceleration ($3m/s^2$ longitudinally and $1.5/s^2$ laterally).

We then estimated whether the design questions would be met for each of our eight concepts to obtain a sum. We decided to move forward with concepts that achieved the highest sum for our initial screening. These concepts were modifying the strength, location, and quantity of tethers in any fashion, modifying the magnets in the same manner, a jerk dependent latch system, and a spring loaded tether detach system.

We wanted to create criteria based on our specifications that we could use to differentiate between our concepts. We created four categories, with imperative, significant but not critical, nice to have, and optional requirements. The assigned weights were 9, 6, 3, and 1 respectively. We wanted to analyze the concepts heavily in favor of the most important requirements. Our must have questions were chosen as the imperative criteria. For the significant but not critical criteria, we chose withstanding 1000+ cycles and remaining attached in different conditions (weather). For nice to have criteria, we chose one person to remount, can be done in two minutes, and all parts remaining in our height profile. Finally, the cost requirements and remounting without tools were chosen as optional. We implemented these criteria into a Pugh chart with our concepts receiving a score of 0, 1, or -1 whether they met the criteria better or worse compared to the existing UFOnano design, shown below.

Criterion	Weight	Baseline (2 tethers and magnet)	More/stronger/change location tethers	More/stronger/change location magnets	Jerk dependent latch	Spring loaded tether detatch
Under no circumstance void the warranty or applicable insurance policy	9	0	0	0	0	0
Remains attached to the UFOnano 95% of the time when accelerating at 3 m/s^2 longitudinally and 1.5m/s^2 horizontally	9	0	1	1	1	1
Pedestrian dummy must be released from mount after experiencing 100 kgf in X and Y directions at 2.5 feet off the ground	9	0	0	0	0	0
Fulfills all applicable NCAP standards	9	0	0	0	0	0
Mount should withstand 1000+ cycles	6	0	0	0	-1	-1
Remains attached despite differences in condition (windy, snowing, etc.)	6	0	1	1	1	1
1 person to remount	3	0	0	0	0	0
Can be done in under 2 minutes	3	0	0	0	0	0
All physical parts should remain within the 20mm-65mm profile	3	0	0	0	0	0
Entire mounting system costs less than $300	1	0	1	1	1	1
Replacement common failure parts must cost less than $25	1	0	-1	-1	-1	-1
No tools necessary to remount	1	0	0	0	0	0
TOTAL (weighted)		0	15	15	9	9

Figure 5. Pugh Chart for evaluating design concepts

None of the designs affect the warranty policy since the robot is not being modified internally. We expect that the magnets and tethers at the mounting interface between the dummy and carrier can be modeled as a spring mass system with an effective stiffness coming from each tether and magnet pair we add. All

designs were rated greater than the existing design for the secureness requirement, since additional tethers, magnets, springs, and latches will increase the total effective stiffness at the interface. We also expect all of the designs to more reliably remain attached during weather conditions for the same reason.

The magnet and tether modifications were rated the same as the baseline design for detaching upon vehicle impact because both will be designed to have the magnets disconnect at a lower force, which we will select from our future engineering force analysis and empirical testing. We also rated the jerk latch and tether detach mechanisms as the same because they can be designed to unlatch at a force slightly less than the impact force. We expect all of our designs to meet this requirement just as well as each other, which is why they all received the same score of 0. If the unlatching mechanism is designed properly, we can expect it to unlatch reliably almost all of the time. When the carrier is accelerating, all of the designs do not affect the deviation between the desired testing speed and measured speed, rate of change of yaw angle, and lateral deviation. This is because we are not obstructing the area near the sensors of the UFOnano that are used to iterate its speed, yaw, and lateral deviation. Therefore, all of our concepts are applicable for NCAP testing.

The jerk latch and tether detach mechanisms were rated inferior than the baseline for the durability requirement because we expect them to fatigue more rapidly from high loading and stress experienced on the springs, latches, and tethers during vehicle impact. This is the greatest risk that could change the scoring decision, as both of these concepts were rated 6 points lower than the tether and magnet modification concepts. While the Pugh chart suggested a modification of the tethers and magnets, since the scores were very similar and volatile to a flip in any of the must have questions, we decided to look at some of the risks associated with each concept failing.

We conducted a failure modes and effects analysis on each concept, where the likelihood of failure, likelihood of detection, and severity of the failure effects were found for each concept. Multiplying them yields the total risk on the public for a design failure. We wanted a concept that is unlikely to fail, and if it fails, it does not affect others negatively and is detectable beforehand. We created a chart featuring the total risk of each design, shown below.

Design	*Failure Mode*	*Failure Effects*	*Failure Causes*	*Likelihood of Fail*	*Likelihood of Detection*	*Severity*	*Risk*
Baseline (2 tethers and magnet)	Early release when jerking	Hinder test productivity and need to replace tether and magnets	Insufficient stiffness	**9**	**5**	**2**	**90**
More/stronger/change location tethers	Early release when jerking	Hinder test productivity and need to replace tether and magnets	Insufficient stiffness	**5**	**5**	**2**	**50**
More/stronger/change location magnets	Early release when jerking	Hinder test productivity and need to replace tether and magnets	Insufficient stiffness	**3**	**5**	**2**	**30**
Spring loaded tether detatch	Failure to detach (release) after impact	Damage to spring, tether, and vehicle	Mechanism does not detach when desired, components may be designed improperly	**4**	**5**	**7**	**140**
Jerk dependent latch	Failure of latch (release) after impact	Damage to latch mechanism and vehicle	Mechanism does not detach when desired, components may be designed improperly	**4**	**5**	**7**	**140**

Figure 6. Failure Modes and Effects Analysis for each design

The failure mode of the magnet and tether modification designs was early release of the dummy when jerking, which was our initial design problem from Mcity. However, this failure is not severe, since it does not damage any parts and pose a high safety threat to the testing operators. The force required to have the magnets detach and lead to early dummy release is predictable based on the acceleration of the carrier, but testing is required to find that threshold for cardinal directions. Because we are modeling the tethers and magnets as a spring mass system, we expect this failure to occur less with tethers that have their strength, location, and quantity modified to provide improved stiffness. But we thought modifying the magnets would perform better since the dummy falling off is due to the magnets disconnecting first rather than the tethers deforming. Because of this, we gave the magnet modification design the lowest likelihood of failure, at a value of 3, compared to 5 for the tether modification.

On the contrary, for the latch and detaching systems, the failure comes from not detaching the dummy from the carrier during vehicle impact. This is a completely different failure mode, and is much more severe. The mounting mechanism, parts, and vehicle can be damaged, and it is much more hazardous for operators because of debris. We rated this a much higher severity of 7. While we think this is unlikely to happen in our designs, we understand that it overheads a higher risk than the dummy falling off the robot prematurely. Based on our initial risk analysis, we model the magnet and tether modification concepts to have the least risk and the unlatching mechanisms to have the most.

Instead of trying to determine whether to modify magnets or tethers, we thought about integrating both of these concepts into our alpha design since they both performed similarly for meeting our reliable (REL) and impact condition (IC) requirements, and having low failure risks. They work very well in unison because we can manufacture mounts which can hold potential magnet spots onto the existing magnet holes on the UFOnano. An additional tether from the neck of the dummy can be added for each new magnet position on the carrier. The positions of the magnets and angles of the tethers to the flat and vertical planes can be easily modified and iterated on to meet our reliable and impact condition requirements.

The first solution we considered was modifying the material properties of the tethers. However, this design is not ideal since the magnets pulling at certain forces is the bottleneck of the dummy detaching from the carrier, rather than the tethers yielding. From force analysis, we know that the angles between the tethers and the flat and vertical planes most impact the tension on the tethers and the risk of magnet separation failure. This is why we chose a modification of magnets and tethers for our alpha design. We don’t expect to fixate on this idea, but the location of the magnets and tethers can be varied in so many ways that we can iterate upon our previous locations to meet the requirements.

Selected Concept - Alpha Design

To increase the magnetic attachment force of the UFOnano robot while still meeting geometric, structural, and overrunning constraints, additional magnet mounting features will be integrated into both the front and rear of the UFOnano robot. The purpose of these new features is to increase the available magnetic holding force without making any permanent changes to the base chassis or interfering with any of the functional components already present on the UFOnano robot. The front feature will be a machined mounting block which will attach directly to the pre-existing threaded magnet mounting locations, while the rear feature is a revised battery cover which includes additional magnet mounting capabilities. Both of

these components use pre-existing threaded interfaces to provide for serviceability, to keep manufacturing as simple as possible, and to avoid making any unnecessary structural changes to the UFOnano robot.

The front mounting block was designed so that the magnets would sit flat against the 65 mm maximum allowed height established by the higher rear plane of the UFOnano robot and designed to meet the overrunnability requirements. The mounting block's design meets this requirement by ensuring that the mount does not protrude above the allowable limits, thereby avoiding any potential interference with any vehicle interactions or creating any excessive impact loads when the mount comes into contact with a vehicle tire. Chamfered surfaces were created along the edges of the mounting block to enhance the overrunnability by decreasing any sharp transitions, and providing a smooth force transfer path should the mount come into contact with a vehicle component. The chamfered surfaces will help to decrease any stress concentrations, and improve the durability of the mount under repeated loading. The mounting block will be attached to the UFOnano using three pre-existing threaded holes, (one central attachment point and two side attachment points). The use of the three attachment points will assist in the even distribution of the applied loads, decrease the possibility of localized overstress of any individual threaded attachment, and prevent the rotation of the mount under the applied magnetic and tether forces. In addition, the magnet mounting surface is oriented at an angle of 7° relative to the horizontal. The orientation of the magnet mounting surface was chosen to allow the tether to attach to the magnet surface at a right angle. This orientation will maximize the magnetic holding force by positioning the applied load with respect to the magnets' highest holding capacity, and minimize any shear components that could cause the detachment of the tether.

The rear modification consists of a revised battery cover that includes additional magnet mounting capabilities, and maintains the full functionality of the existing enclosure. The height of the rear magnet mounting surface will be limited to the same height as the rear antenna to ensure that the rear modification does not violate any of the geometric or operational constraints. The battery cover will be secured to the UFOnano robot using the existing threaded hole located at the rear of the robot, in addition to the four threaded holes located at the corners of the battery cover. The use of multiple attachment points will provide adequate structural stiffness to withstand the increased loads generated by the additional magnets. The rear attachment point which is reusing the original magnet hole will be supporting the largest load of the 5 mounting screws due to its furthest distance from the dummy, therefore having the highest moment. The use of multiple attachment points will distribute the applied loads across multiple attachment points, thus decreasing the probability of attachment point failure, thread striping, or excessive deformation. The magnet mounting surface on the rear cover is oriented at an angle of 8° relative to the horizontal to accommodate the slightly different spatial relationship of the rear magnet mounting surface to the tethered target, to ensure that the magnetic force vector is properly aligned, and to maximize the retention performance.

The exact number, size, and configuration of magnets to be used for both the front and rear mounts are currently being evaluated and will be determined based on the results of the quantitative magnetic force calculations, and the ultimate selection of the magnets. The magnitude of the holding force of the magnets required must exceed the maximum expected tether load with an appropriate margin of safety, while remaining within the geometric and structural constraints of the UFOnano robot platform. Consideration will be given to the pull force rating of candidate magnets and dynamic effects during the calculations.

The results of these calculations will enable the determination of whether to select a single large bar magnet, or multiple small circular magnets arranged to maximize the effective holding force, while maintaining structural integrity and manufacturability. This method will ensure that the final design is optimized for both performance and reliability, and remains compliant with all applicable system requirements.

Problem Analysis: Anticipated Challenges

The primary technical challenge in this project is reflected by the "Goldilocks Problem" which characterizes our need to achieve a precise retention force capable of preventing premature detachment and controlled release during vehicle impact. This constrains our design flexibility as the manipulation of one performance metric has the potential to negatively impact another. This, as well as the consideration of implications imposed by other critical components, has allowed us to successfully evaluate the risks and uncertainties that could impact the overall performance and feasibility of the final design:

Risk	**Impact**
Insufficient retention force	Dummy detaches prematurely during acceleration; reduced testing efficiency and reliability
Excessive Retention Force	Dummy fails to detach at all; risks damage to UFOnano and vehicle
Off-axis loading	Unexpected detachment due to misaligned forces/unaccounted-for torque
Environmental effects (wind, moisture, debris)	Reduced magnetic performance and inconsistent behavior; testing failure
Tether misalignment or slack	Uneven load distribution and instability
Material wear over time	Degradation of performance and durability across cycles

The most significant uncertainty proposed by the project is in regard to the actual forces experienced at the mounting interface during operation. While simplified models and force analyses can estimate inertial and wind loads, the combined effects of acceleration, wind, off-axis forces, and dynamic motion prove difficult to predict without experimental validation. In addition, our magnetic behavior during real-world operation (unaccounted for surface imperfections, misalignment, shear loading, etc.) introduces further uncertainty that needs to be considered.

To address these uncertainties, our current design incorporates several mitigation strategies:

- The inclusion of an adjustable magnet configuration allows us to continuously tune retention force
- The pretensioning of the tethers mitigates the possibility of load distribution uncertainties and tether slack
- The use of environmental testing enables us to capture realistic loading conditions

- The incorporation of iterative testing is crucial in redefining force thresholds after empirical testing

These features allow the team to continuously refine the design based on measured data rather than purely relying on uninformed assumptions. Though these critical uncertainties have been addressed, the most critical task for the team to complete prior to successful conclusion of the design cycle is to experimentally define the acceptable retention-release force window. To complete this, we will be measuring the detachment forces of our prototype mount under multiple loading conditions, specifically focusing on obtaining the pull, shear, and off-axis release data across various mounting interface conditions (wet, dry, dirty). In addition, due to the interdependency expressed earlier, we will also be ensuring that the increased retention is not characterized by the introduction of new failure modes. By successfully addressing these challenges, we'll be able to verify that the final design behaves consistently across repeated cycles and is safe under real-world testing conditions.

Project Plan

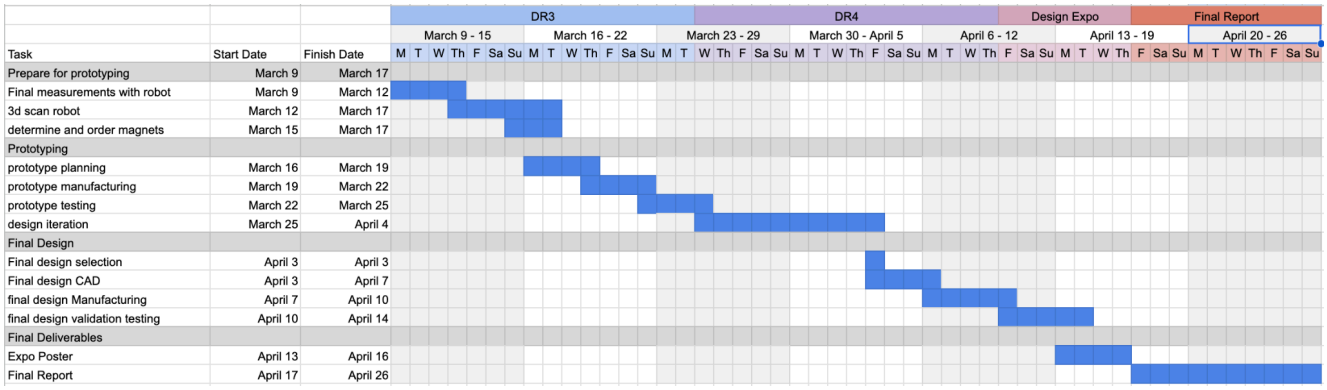


Figure 7. Project schedule

In order to ensure the successful completion of our validated mounting system by the Design Expo, we've developed a structured execution plan emphasizing task ownership, risk mitigation, and iterative validation. This plan serves to tackle the technical challenges of our project, specifically allowing us to address the uncertainties regarding the retention-release force window and our need for empirical validation. Therefore, each major task has been delegated to a specific team member to ensure accountability and the concurrent development of critical components of the design within our allotted time requirements.

Task	Description	Owner(s)	Deadline
Geometry Finalization	Finalize magnet positions, tether layout, and CAD geometry	Drew	3/23 - Done
Magnet Characterization	Measure detachment forces of selected magnets (normal, shear, off-axis)	Amogh	3/26 - Done

Tether Design	Define tether material, length, and method of securement	Drew	3/26 - Done
Prototype Manufacturing	Machine and assemble mounting components	Drew	3/28 - Done
Lab Testing	Perform controlled force and durability tests	Amogh	3/29 - Done
Environmental Testing	Evaluate performance under wind conditions	All	4/14 - Done
Iteration	Refine design based on test results	Drew	4/4 - Done
Final Validation	Verify all specifications are satisfied	All	4/14 - Done

To avoid exposure to late-stage compression, we have also defined several critical checkpoints for our project:

- Prototype Readiness Gate - Mounting components manufactured and assembled; initial functionality confirmed
- Data Collection Gate - Experimental data collected for retention, detachment, and environmental performance
- Design Freeze Gate - Finalized geometries and configurations based on iterations from validated test results
- Final Validation Gate - Successful performance of all critical specifications through repeatable testing

By ensuring that our design efficiently progresses from prototype to validated solution, this structured execution plan allows the team to remain on track while streamlining potential responsibility and scheduling uncertainties. As our final deliverable, we aim to include a fully functional mounting system prototype with validated performance in regard to the defined specifications, as well as the supporting engineering analysis, experimental results, CAD models, and manufacturing documentation.

Engineering Analysis

Our engineering analysis methods to test our design's capacity to meet our most important specifications are first principles and empirical testing. As mentioned, we want our redesigned mount to provide sufficient retention force in all cardinal directions to avoid the dummy's release from the robot prior to testing. We also want to avoid the risks associated with an excessively high retention force, as mentioned in our failure modes and risks analysis. These requirements can be modeled as designing the dummy to detach during a range of force values in each direction, and ensuring that the lower force value is higher than the loading conditions from acceleration, wind, etc. with a safety factor, and that the higher force value is lower than the loading conditions from vehicle impact with a safety factor.

We can model forces from acceleration of the robot and wind with reasonable accuracy using free body diagrams and force/moment equilibrium. While a force model does not account for all of the environmental conditions (such as snow), we used it, with a safety factor, as our initial confirmation of the design. Because we have access to Mcity's testing facility and the UFOnano, our actual verification and validation testing will be performed there. To evaluate our ability to avoid the dummy's release prior to testing, refer to REL-01, REL-02, and REL-03V. These tests will be performed at the Mcity testing facility using the maximum possible acceleration and deceleration of the UFOnano. To evaluate our ability to have the dummy release during vehicle impact, refer to IC-01V and IC-02V. These will be performed at the Mcity testing facility using a calibrated force gauge. Because our final verification methods are based on empirical testing of our design, it is only logical to use them to rigorously evaluate our prototypes in the same way that we will verify them.

For each magnet and tether configuration design, we will perform an initial force/moment balance analysis to ensure that we meet our reliable and impact condition requirements. Having met these with a safety factor, we will build the prototype and perform our verification testing in the Mcity facility, and continuously iterate on the design. We believe our most effective path is to design prototypes, perform our initial force analysis screening, build and test the prototypes using our verification testing, and iterate the design. This will allow us to meet our V&V requirements before the design expo.

Force Analysis

To assess our design concept, we wanted to perform an initial theoretical force analysis to model how the system would react to the carrier accelerating for our reliable requirements. For this analysis, we chose our design with four total magnet and tether pairs, with two magnet pairs on our magnetic mount and two pairs on the battery cover. Our CAD model for the UFOnano base with the magnets is shown below.

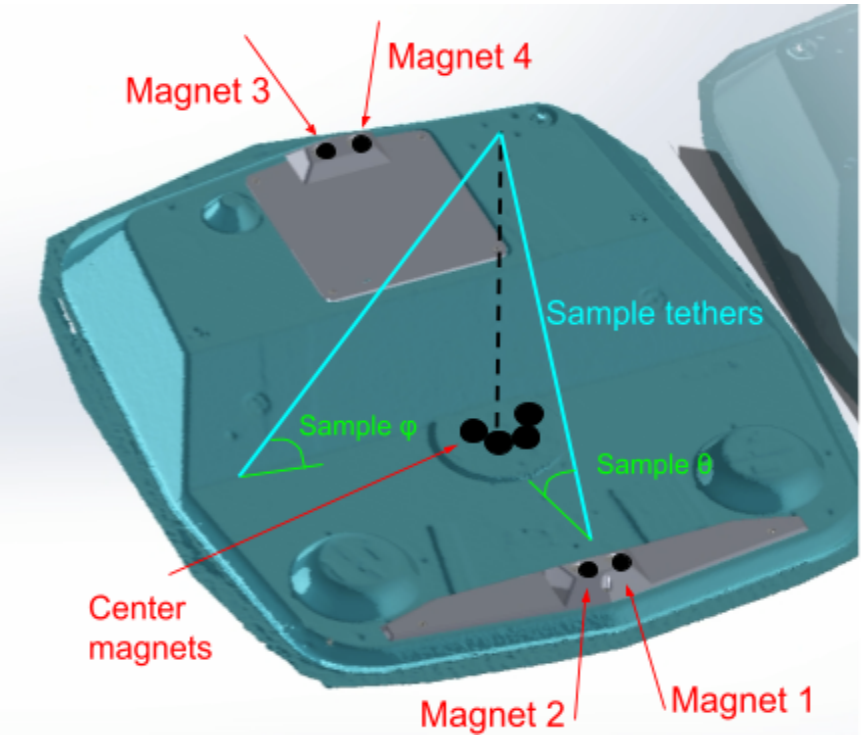


Figure 8. CAD prototype with labeled magnets and FBD angles.

Our design has four tethers in total. Tethers 1 and 2 connect to the front of the base plate and tethers 3 and 4 connect to the back of the base plate. The tethers attach to the magnets and are associated with each magnet. The tethers extend upwards and are securely attached to the neck of the dummy. There are four magnets near the center of the base plate, where the dummy attaches to the plate via the clear pole. Our design consists of a modified battery cover, with two areas to mount magnet pairs 3 and 4, and a modified mount that contains magnet pairs 1 and 2. The blue tethers are not part of our design, but are sample tethers for the purpose of viewing demonstrations. The θ and φ angles are the angles that we used to calculate the vertical component of the tension in the tethers for our force analysis. They are enlarged and shown on the blue sample tethers for only viewing purposes. They are found from and are related to the tethers connecting the magnets to the neck of the dummy, but are clearly enlarged here on the sample tethers for the sake of clear demonstration.

Some important parameters that must be modeled in our design are magnet pulling forces, wind, and tether behavior. A magnet creates a magnetic field, and the resulting pressure is the magnetic flux density squared divided by the permeability of space. The pulling force is found from multiplying this with the area. If the perpendicular force exerted is more than the pull force, it detaches. If the parallel force is more than the pull force times friction, it detaches. In our design, we measured the angle of the tethers from the horizontal plane and angled our magnet mounting holes to be the complementary of said angles (8.5 and 9 degrees). This means the tether tension is perpendicular to the magnet, so they can resist forces until the maximum pulling force. We modeled tethers as two force members that can only experience tension loading. When they experience compression loading, they slack and do not transmit forces. Because they are two force members, the tension is directed along the tethers. Finally, we modeled wind as a point force acting on the dummy, located at the center of pressure. Wind exerts a dynamic pressure (q) on the contact area, equal to $q = 0.5\rho v^2$, where ρ and v are the air density and velocities. The total wind force is $F = q(C_d)$(Area), where C_d is the drag coefficient of the dummy.

Next, we created a free body diagram of all of the forces involved in the model, shown below.

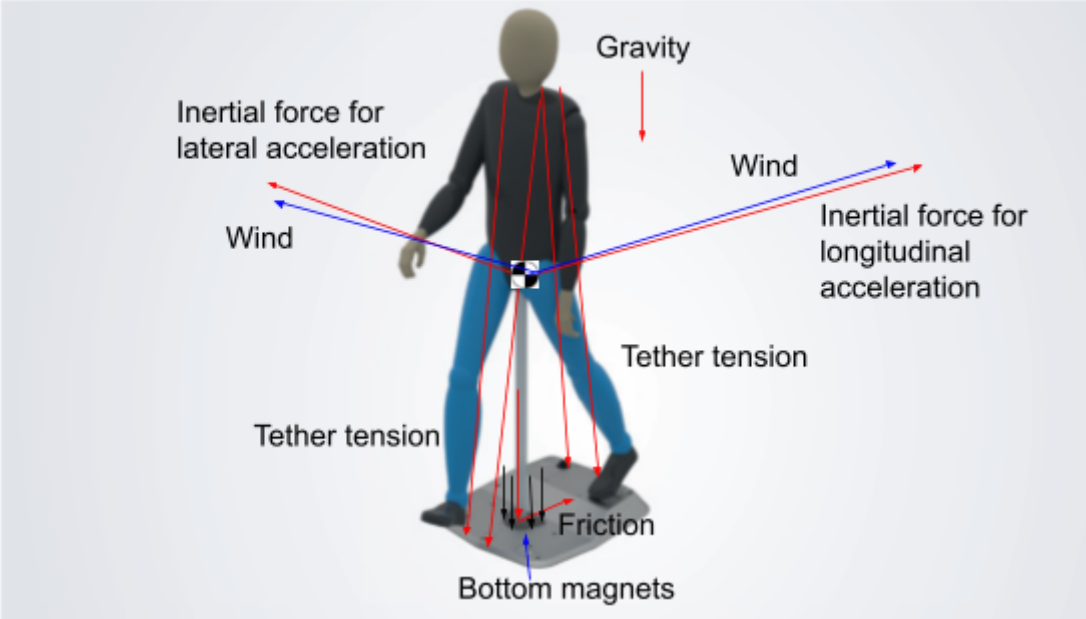


Figure 9. Locations of forces used in the free body diagram

Our force analysis consists of a horizontal force and moment balance. The moment balance is taken at the center of the tube, at the center of where the bottom magnets attach.

Let us call the dummy mass M_D (kg), carrier acceleration a (m/s^2), the angles between the tethers and the flat plane θ_1, θ_2, θ_3, θ_4, the angles between the tethers and the vertical plane φ_1, φ_2, φ_3, φ_4, the tether tensions T_1, T_2, T_3, T_4 (N), the wind force F_w and the dummy center of gravity height h (m). The tethers will have the same young's modulus since we will be purchasing them.

When the carrier accelerates in any direction, this acceleration can be modeled as an inertial force of $M_D a$ in the opposite direction. There is also a F_w wind force, $M_D g$ downward force, tether forces, normal force at the interface, downward magnet forces on the center of the carrier, and frictional forces at the same location. The horizontal force balance equation is $\sum T_i cos(\theta_i) + F_{friction} = M_D a + F_w$. If the frictional force is greater than μN, the center magnets fail by sliding.

In addition to forces, a moment is applied when the carrier accelerates. There is an inertial moment of $(M_D a + F_w)h$, which is resisted by the tethers and magnets at the center. The moment balance equation is $(M_D a + F_w) * h = \sum T_i sin(\theta_i) x_i + \sum$moment from friction + $\sum$moment from center magnet forces. Here x_i is the horizontal distance from tether (i) to the bottom magnets at the center of the carrier. To model the moment caused by the friction and center magnet forces, we unlatched the tethers and applied a force at the center of gravity of the dummy until it tipped. The force was lower than the frictional force in the horizontal direction, and the magnets did not slide, so the failure was from the moment being higher than the moment contribution by the friction and magnets. The moment by friction and center magnet forces is that force multiplied by h. We performed our moment balance for acceleration in each of the four cardinal

directions. These gave us the equations of motion to calculate the required magnet pulling forces to meet our reliable requirements. When the carrier accelerates in any cardinal direction, two of the four tethers are in compression, so they slack and do not carry any moment. The total moment is balanced by the two remaining tethers in tension and the frictional and magnetic forces at the center of the base plate. The moment contribution from the tethers is the (equivalent vertical load)(moment arm)(tension in tether). The force analysis calculations are described in detail in Appendix B.

In summary, we obtained required magnet pulling forces of 43N for forward acceleration, 26N for backward acceleration, and 36N for lateral acceleration in each direction (all with a safety factor of 1.3). We will use a very thin ferrous carbon steel alloy on top of the magnet. We have another requirement of having the dummy detach from the mount upon experiencing a force of 100N in any cardinal direction at the center of gravity to avoid potential damage to the vehicle, which we still meet.

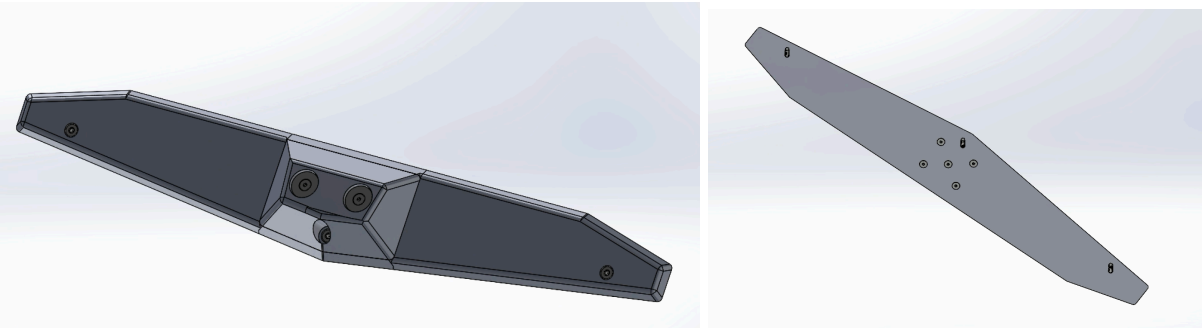
A high level of detail was chosen for the force analysis to model our reliable and impact condition requirements because small inaccuracies or errors in angles, lengths, and forces can cause a significant error in our final result. Because we are using this to screen our concepts, and because we are using first principles to model the problem, it is imperative that we do it accurately. We are confident in our analysis, and if we find mistakes, we will immediately iterate it. This analysis attempts to correlate the two most important requirements that we will eventually test empirically to physics concepts such as forces and moments. We do not think any technical issues are overlooked, as we accounted for wind as well as a reasonable safety factor. The analysis can be completed efficiently and we have time to iterate it if necessary.

Final Design Description

The final design is an improvement on the current hybrid magnet-tether mounting system that secures the dummy to the UFOnano platform during operation. The design features an increase in the retention force through the incorporation of additional, stronger magnetic interfaces while also increasing the number of tethers to improve stability and distribute loads. The system aims to successfully satisfy our two opposing requirements of mitigating premature detachment, while ensuring reliable, consistent release under impact conditions.

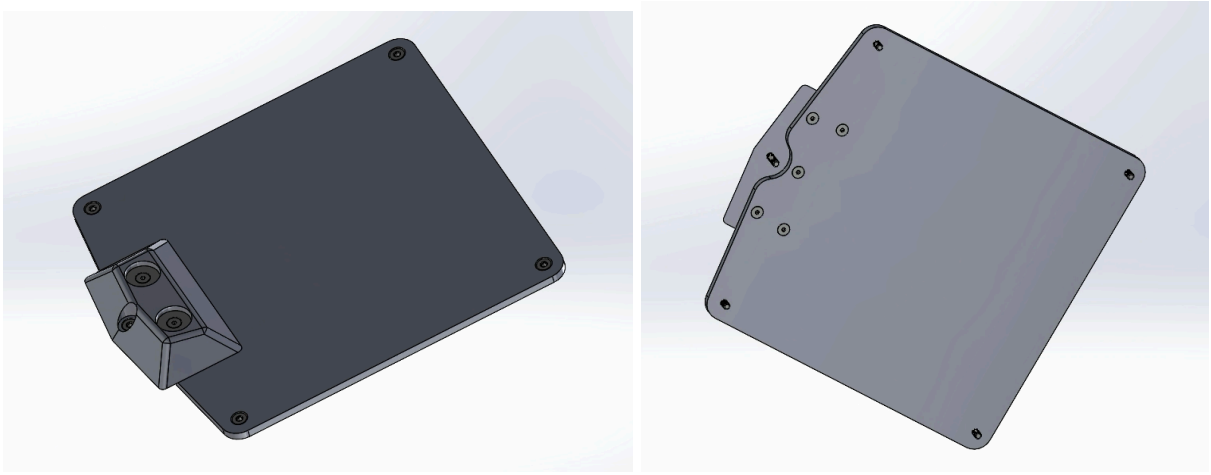
Our final design consists of three primary assemblies: the front adapter, the rear mounting battery cover, and the two-tether system.

The front adapter plate is an extension that will be mounted to the front region of the UFOnano baseplate. This mounting feature will increase the effective magnetic contact area as well as retention force. It will also be where the 2 circular magnets are housed. In order to ensure stability, the front adapter plate will mount into 3 former threaded magnet holes on the robot: in the front and at the edge of the winglets. The front adapter plate is made out of 2 main components to ensure manufacturability- the flat base and the angled head. These components are joined by 5 countersunk bolts that will sit flush against the robot. Both the flat base and angled head are designed with heavy use of fillets and chamfers to ensure the overrunability specifications are met. The mounting planes for the magnets in the front are set to a 9.5° angle so the magnets will only experience a force normal to their respective seating. The front adapter plate is shown below.



Figures 10 and 11. CAD of final design of the front plate assembly.

The rear mounting battery cover is a modified version of the current battery cover that incorporates additional magnets while maintaining compatibility with the existing mount profile. Similar to the front adapter, the rear mounting battery cover is made of 2 main components: the flat battery cover and the head which houses the magnets. The current battery cover will essentially be copied and remanufactured but with the 5 countersunk holes in the bottom for the flat battery cover. As shown below, threads on the robot that house the original magnet will be reused with the new cover in order to ensure the cover will not be sheared out of its 4 corner threads. The mounting plane for the magnets in the rear cover are set to an 8° angle so the magnets will only experience a force normal to their respective seating. The rear mounting battery cover is shown below. To fasten the magnets to the plates, a threaded hole is created inside each magnet hole, where a fastener would be inserted into. The fastener's chamfered head diameter is larger than the inner diameter of the magnet, ensuring that the magnet is securely attached to the plate. We want to have only the magnetic steel piece that is connected to the magnet and the tethers to detach from the plates, so that it can be quickly reattached between testing.



Figures 12 and 13. CAD of final design of the rear battery plate assembly.

The dual-tether system consists of 2 two-tether systems connecting the dummy to the front and back components that allow the dummy to move without detachment during UFOnano operation. There will be magnets at the end of these tethers that interact with the other components and allow for the distribution of forces across the system.

These components work cohesively to enable the mounting system to resist external loads through a combination of magnetic forces, friction, and tension. The magnetic forces act normal to the mounting surface, and generate a normal force that allows for retention at the interface between the dummy and

UFOnano. This retention resists the motion due to acceleration and wind-loading typically experienced in real-world testing scenarios. The tethered system improves on the current tensile strength needed to allow vertical retention when the dummy is subject to inertial loads. In addition, by locating our tether attachment points at both the front and rear we reduce moment-induced detachment while maintaining stability. The precise angling of the magnetic housings on the front plate and modified battery cover allow the tethers to also resist moments generated by forces acting at the dummy's center of mass. The combined action of the magnets and tethers effectively counteract the forces and moments created by the external loads, specifically the inertial forces due to acceleration and aerodynamic forces from the wind. By selectively choosing our magnet strength, we are also able to ensure that this combined retention force is in effect until the applied force exceeds the retention capacity, at which point detachment occurs.

Shown below is the front adapter, the rear mounting battery cover in grey, with a 3d scan of the UFOnano in teal.

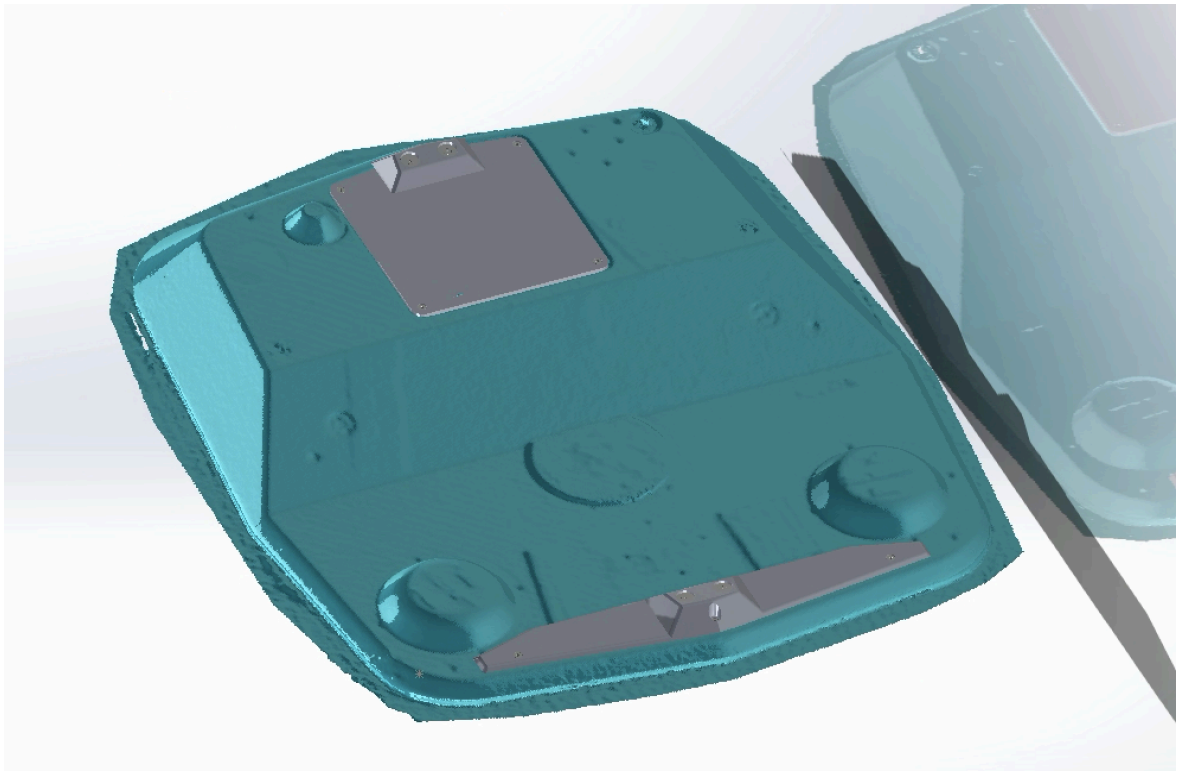


Figure 14. Front and rear mounting plates on the UFOnano CAD

As shown below, the overrunability specification is met by both the front and rear mounting systems living within their respective maximum areas. The rear mounting battery cover is no higher than the antenna shown in the scan (19.6mm), and the front adapter is much shorter than the 65mm max height allowed. Shown below is a side view of the robot, with our maximum heights clearly being less than antenna and maximum height allowed, allowing it to be overrunable.

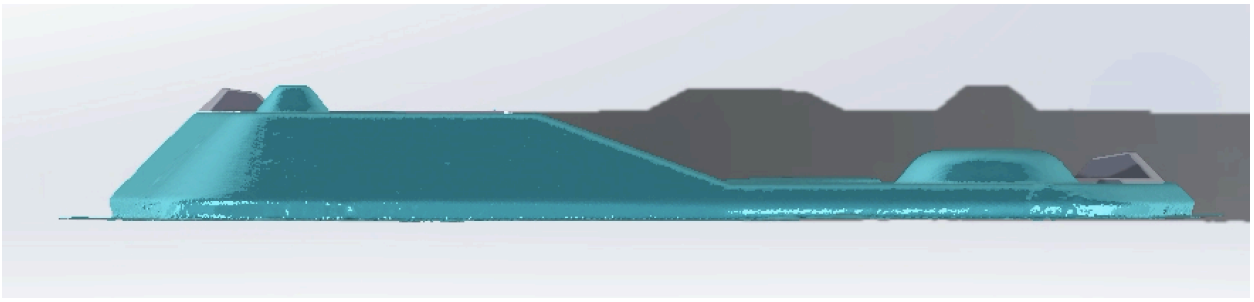


Figure 15. Comparison of heights on the UFOnano CAD

Aluminum was selected as the material for both of these plates because it not only has the highest stiffness to weight ratio compared to magnesium, steel, and titanium, but it is cheap, highly corrosion resistant (does not rust), and matches the already existing material. Thus there will not be corrosion at the interface between the two metals when we install our front adapter and rear battery cover to the robot. Ensuring this is extremely important to meet our durability requirement, since our design will need to work effectively for many cycles.

Description of Verification and Validation Approach

Verification and validation are similar processes, but serve different and critical purposes in determining the overall success of a design. Verification is a process to determine whether the solution works the way we designed it to or not. Verification is connected primarily to the engineering specifications of the design, and confirming that the design works as intended. Validation, on the other hand, is concerned with whether or not the design addresses the problem we intended to solve. Validation deals with the user requirements more so than the engineering specifications to ensure that whatever was designed actually fulfills the design criteria on a high level [29]. It's entirely possible to have verification without validation and vice versa, for various reasons, but having both is much preferred than one or the other.

Verification and validation is important for all requirements and specifications, but it's crucial for the most critical requirements and corresponding specifications. The most critical requirements for our design are reliability, detachability, and overrunnability.

Before doing our verification tests, we wanted to make sure that the magnet connections were behaving accurately compared to the force analysis. We placed a force gauge on the tether above each magnet and pulled directly in the line of the tethers to measure the connection force. We initially ordered 65N magnets and obtained an average connection of 30N. We then ordered 80N magnets and after 3 trials for each magnet, we obtained an average force of 52N. The force analysis suggested that 43N was sufficient for our acceleration and deceleration requirements with a 1.3 safety factor, so we could start testing.

The verification plan for the reliability requirement utilizes the functional testing and environmental testing method of verification. We mounted the dummy on the UFOnano with our mounting design and conducted repeated tests in various conditions to verify the dummy remains secured to the robot.
For the first test, we had the robot accelerate from rest at $3m/s^2$ to its top speed of 5.55m/s, and then decelerate to rest with a deceleration of $3m/s^2$ as well. This test was done in the forward direction. A successful test would see at least 19 out of trials passed, where a passed trial consists of no premature

detachment during the duration of the trial. We performed the test and premature detachment did not occur during any of the 20 tests. A few videos of the procedure are shown in the google drive.

The second test would have the robot accelerate from rest at 1.5m/s^2 to its top speed and decelerate to rest again with the same passing and success parameters. However, this test is done in the lateral direction. Unfortunately, when setting up for this test, something broke in the drivetrain system of the UFOnano and the right wheel was unable to rotate, causing the robot to not move properly. Alex said this might take weeks to solve, since he would need to place orders for spare UFOnano parts, which come from Europe. We were not able to conduct this test, but are very confident that we would meet all 20 trials, since we easily met all 20 forward trials. Additionally, our force analysis with 43N connection forces provides a safety factor of 1.3 for acceleration and wind in that direction, and we measured 52N connection forces for our final design. We also wanted to conduct these tests after obtaining the wind speed with a calibrated anemometer to record the wind speed to factor into our analysis. However, we did not have access to a wind tunnel large enough to fit the UFOnano and dummy and due to time constraints, were not able to perform this test. Alex did say that one day it was very windy and it held up in the wind miles better than the previous model. Future work is needed to test this requirement properly, and waiting for a day with around 5m/s wind measured by a calibrated anemometer to test the design is probably the most realistic way to move forward.

The verification plan for the detachability requirement also utilizes the functional testing method of verification. We conducted two tests for this requirement, one with a force gauge and one with a vehicle. The force gauge test consisted of using a force gauge at the dummy's center of gravity to pull the dummy off the robot in all cardinal directions. The robot was grounded and the test conductor used a steady force as opposed to a jerk force. A successful trial would see the dummy detach from the robot at an experienced force less than 100N. This test will be successful if 5 consecutive trials are passed. We performed this test and obtained average values of 39N pulling forwards, 56N pulling backwards, and 36N pulling sideways, easily passing this test.

The vehicle test had the robot stationary and the vehicle approach and strike the dummy at around 5 m/s. There were two iterations of this test, with the dummy facing each of the cardinal directions. Each iteration of the test will be successful if 5 consecutive trials where the dummy detaches are passed, and the vehicle test as a whole will be successful when all four iterations are successful. Alex drove the vehicle and struck the dummy at 5m/s, and the dummy detached for all tests. A video of one impact is also shown in the google drive.

The verification plan for the overrunnability requirement utilizes the inspection method of verification. This test consists of 5 measurements of the dimensions of all rigid components of our design with calibrated calipers. This test passes if the average of the values is within the "overrunnable envelope". We defined the "overrunnable envelope" as being contained within the existing rigid dimensions of the UFOnano, which are shown in Figure 1 on page 2. The dimensions we are most concerned with are the 20 mm and 65 mm bounds, as exceeding those would lead to a potential for damage to the vehicle, the robot, and the operator. The final dimension measurements were 45.8mm front, and 20.8mm rear, resulting inside our bounds. The vehicle test described above is also part of the overrunnability verification plan. Alex has a Ford Mach-E for Mcity testing, and that was the vehicle we used for the vehicle test. Upon

completion of the vehicle test, inspection was used on the robot, our implemented mounting system, and the vehicle. For the robot and our implemented mounting system, any cracks, chips, fractures, or other deformations visible to the naked eye will fail the overrunnability portion of the vehicle test. For the vehicle, any dents, scratches, chips, or other deformations will also fail the test. Any "significant" damage, or damage that negatively impacts the vehicle's functionality in any way, will fail the test as well, but this damage is especially not acceptable in our testing environment. The mitigation strategies in place to avoid any significant damage are to strictly remain within the overrunnable requirement, and to have Alex be the only operator of the vehicle. Alex performed this test driving the Mach-E at 5m/s. Alex, having done inspection, said that there was no visible damage to the mounting system and vehicle. We also were unable to find any visible damage as well, passing this test. We forgot to take photographs of the vehicle after impact, so this test can be repeated in future work with clearly documented before and after photographs to ensure no damage to the mount or vehicle occurred.

Lastly, our final important requirement was that the design should be simple to remount, and one person should be able to mount the dummy (after detaching) with no tools in under two minutes. We had Drew perform this test for 3 trials, and he completed them with an average of 17 seconds, well under the 2 minute requirement.

Some of our other important, but not critical requirements were having the mount being durable by withstanding 1000+ cycles, not voiding the insurance or warranty policy of the UFOnano by any means, a total cost of items in the Bill of Materials under $300, a cost of each item in our Failure Parts List under $25, and that the UFOnano would fulfill the temperature wind speed, and accuracy of carrier standards specified in ISO 19206-7 for NCAP testing. Our testing and verification method for the durability requirement was to run 100 cycles with double the detachment force (100N) and inspect for cracking, deformation, and loosening, with a pass if none apply. However, we were not able to do this test due to magnet constraints. We had to order the strongest magnets McMaster offered since they did not have the strength as advertised (were 60% lower), not allowing us to test with the higher strength per our requirement. We did not modify the interior of the UFOnano in any way at all, thus we did not void the insurance or warranty policy, passing this requirement. Our total cost of items in the Bill of Materials was $297.14, successfully under the $300 requirement. Our failure parts were the plain carbon steel piece and fasteners, which are well under $25 each. Because Mcity typically tests within 5m/s wind speed and 0 to 30°C ambient temperature, and since we did not modify or obstruct the sensors and accelerometers which track the speed, lateral deviation, acceleration, and yaw of the robot, we also meet the accuracy of carrier standards for NCAP testing.

An important factor to consider when generating verification methods is whether a successful test will truly verify one of your specifications. This is critical because performing verification testing is pointless if you can't be sure the test proves that the design in question has met a specification. We achieved this for each verification test described above. The acceleration test is done at the maximum velocity, acceleration, and deceleration achievable by the UFOnano. This ensures that we are testing the boundary conditions of performance. Knowing that the extremes pass the test prove that less extreme conditions will also pass the test. The 100N value we are using in the force gauge test was generated through first principles analysis, which is a good way to get the ball rolling on designing empirical tests. The 5 m/s that the vehicle is traveling in the vehicle test was obtained through stakeholder interviews. Another important

consideration to make when evaluating verification methods is repeatability. If the verification method can't be replicated, then the design simply hasn't been verified. By performing many trials and clearly outlining our verification method, we have ensured that our methods are repeatable.

Verification and validation methods are distinct in their goals and philosophies but often overlap logistically. For example, the verification test that proves it can withstand 3 m/s^2 of acceleration without detaching prematurely also validates that "the project works as intended under normal and extreme conditions" [29]. It's important as engineers that we don't let this overlap create blind spots where we use verification to imply validation and vice versa. If a product works exactly how we designed it to work and it doesn't solve any problems, we have failed. Similarly, if we create a product that is exactly what someone wants but breaks as soon as the wind blows, we have failed. Knowing where the overlap exists between verification and validation in our specific design context and using it effectively will be valuable throughout the semester.

Validation is focused on the user requirements and whether or not the design effectively solves the problem statement. Our problem statement is tailored specifically to Mcity, so most of our validation would happen with regards to them. In particular, Alex and Jim are the only people who are allowed to operate the UFOnano, and since our problem statement is directly concerning the operators of the UFOnano, their input would be critical. Our initial validation plan was to generate a survey of questions, each pertaining to a user requirement. The answers options would be on a six point Likert scale, with varying language depending on the nature of the question. A six point scale was chosen as opposed to a five or seven point scale in order to omit any neutrality, which is critical for us since our sample size is two people. This validation method is scalable, and if our design were to be used elsewhere the survey would be applicable to those users as well. However, from time constraints, we were unable to send this survey to Alex and Jim. We instead interviewed them regarding each of our requirements and they both said they were very satisfied with our design and it outperformed the previous design. We will send the survey to them soon, and are confident that the survey will be a good indicator of whether or not we designed something that solves the problem because the very people who have the problem are the respondents.

Discussion

Problem Definition

If more time and resources were made available, we would further define the problem by collecting additional long-term data from Mcity testing operations. Though our research allowed us to understand that the major flaw of the current system was the inconsistent retention and premature detachment, more quantitative data on failure frequency, setup time, and environmental effects (specifically snow and rain) would have assisted in our characterizing the severity of the issue. For example, future work focusing on tracking how often the dummy detaches unintentionally after a number of test cycles, how much time was lost per reset, and how the retention changed as a result of multiple impacts or exposure to debris, rain, dirt, low temperatures, etc., could prove significant in developing future modifications to the mounting system.

In addition, the team would allocate more time toward investigating a wider range of testing conditions for the mount. The verification testing we performed allowed us to demonstrate successful retention under our intended conditions, however additional testing could help us characterize the mount's performance under more realistic field conditions, such as various road surfaces (incline or decline), potholes, vibration, wet surfaces, and repeated vehicle drive-overs. These methods would allow us to provide stakeholders with a more cohesive prediction of how the mount is expected to perform across a full range of autonomous vehicle testing scenarios.

Further problem definition could also benefit from the incorporation of more testing involving multiple operators at the Mcity testing facility. This would allow us to verify that the setup and remounting procedures for the mount are equally intuitive for users with different experience levels, further confirming our usability requirement. However, we do not know if this is feasible as Alex and Jim are the only individuals allowed to operate the robot.

Design Critique

The true strength of the final design is its reliable retention during normal UFOnano operation. By passing 20 out of 20 trials for maintained retention during the acceleration and deceleration verification tests, the prototype proves to successfully address the original mounting issue that resulted in frequent resets and reduced testing throughput. Therefore, by keeping the dummy attached unless impact conditions are met, the final design directly improves testing efficiency at Mcity while allowing operators to complete more runs with significantly fewer or no interruptions.

Another strength of its design is its compatibility, manufacturability, and precision. Due to the fact that the UFOnano-dummy interface required accurate dimensions, chamfers, and edges to remain overrunable and fit properly within the dimensioned profile, we chose to have the mounting components CNC milled by the X50 Graduate Shop. Since we did not have adequate CNC training to independently manufacture these parts, the use of Don, a shop professional, mitigated fabrication risk and ensured the final components met the specified tolerances. The use of a machined geometry also eliminates the lack of repeatability that would be characteristic of a rougher hand-fabricated version of the mount.

One challenge presented by the design was that the ordered stock dimensions were slightly different from the dimensions expected by the team. One example is the front base plate being 0.2" less thick than we estimated. Though the final components were still manufactured successfully, this observation highlighted the need to take into consideration supplier tolerances and material dimensions prior to machining. Another challenge present was the inaccuracy of the magnet specifications provided by the supplier. The first magnet order did not provide the intended magnet strength and the replacement magnet also performed below the expected strength. Although we were still able to receive the necessary magnetic retention force using these magnets, in future work we now know to include a safety factor to account for supplier variation.

If we were to redesign the system, the most effective modification would be to make the magnetic retention adjustable. For example, the design could include more interchangeable magnet locations that would allow for the continuous retuning to necessary strength due to potential variations in environmental

conditions, dummy mass, or desired detachment behavior. We would also attempt to add wear-resistant contact surfaces or replaceable pads near the area being contacted by the car tires to improve long-term durability after repeated cycles.

Overall, the final design performed efficiently in regards to the most critical project needs, especially retention during acceleration. The main opportunities for improvement identified are in response to the desire for adjustability and long-term durability that would allow for increased confidence in a wider range of operational conditions.

Risks

Several challenges were encountered during our design process. A main risk identified was the need for manufacturing accuracy due to the need for the mount to remain low-profile, overrunable, and waterproof on the battery plate side. Therefore, small errors in geometry, chamfers, or edges could affect both fit and vehicle interaction. We mitigated this risk by choosing to have the components CNC milled by trained machine shop staff rather than attempting to manufacture precision parts ourselves without the required technical training.

Another risk encountered was supplier uncertainty that arose as the team experienced issues with magnetic strength and stock dimensions differing from expectations. This risked the ability of our prototype being able to provide the intended retention force or fit properly. The team addressed this by testing our critical components and assembled prototype prior to closing out the testing phase.

The main risk associated with this project was the existence of our “Goldilocks” dilemma that characterized the tradeoff between secure retention and safe detachment. If the mounting interface was too compliant, the dummy would detach frequently, minimizing testing efficiency. If the mounting interface was too strong, the system would not safely detach, potentially resulting in damage to the robot and vehicle. The team mitigated this risk through the use of verification testing that allowed us to confirm that the prototype successfully maintained retention during intended conditions while still allowing for controlled detachment.

For the end-user, the main remaining risks are long-term durability, environmental exposure, and potential inconsistent performance after repeated field use. The prototype's successful performance during verification testing proves its effectiveness in regards to stakeholder needs, however, additional testing is necessary to confirm performance after extended cycling and in various conditions. These risks do not prevent the design from being useful, but absolutely should be considered before the design is adopted as the standard mounting solution for long-term sponsor use.

Reflection

Engineering projects have the capability to change the world for better and for worse, and it’s critical to be aware of how a project impacts different aspects of society. Our new mounting system is no exception, and our team kept the societal implications in mind throughout the semester. The new UFOnano mount will streamline the automated brake testing for autonomous vehicles, allowing research to be completed more rapidly and efficiently. This will lead to safer vehicles, and hopefully lead to safer roads as autonomous vehicles are integrated into society. Our design wouldn’t be of particular benefit in a global

marketplace because of the significant barriers to entry. The UFOnano is very expensive, costing hundreds of thousands of dollars, and our mounting system works exclusively for that model. Highly specialized and expensive products don't typically thrive in a global marketplace. There are some social and economic impacts associated with manufacturing and disposing of our design. The necessity of CNC machining lowers accessibility, which could lead to corporations taking advantage of smaller businesses who don't have the resources to purchase their own UFOnano or mount. Our design is recyclable, which is important for disposal. The aluminum 6061 alloy can be recycled, and the magnets don't have a negative impact on the environment after disposal. Some of the tools we used to characterize some potential societal impacts of our design included stakeholder mapping and interviews, environmental impact analysis, and ecosystem maps.

All four team members come from different cultures and backgrounds, and these backgrounds influenced some approaches we took. Peter grew up loving nature, so making an eco-friendly design that minimized waste was important to him. Amogh was interested in physics, and wanted to initially use a first principles force analysis as a proxy to evaluate our alpha design. Dale and Drew have always been interested in cars and doing hands-on engineering work, so the opportunity to actually test the mount and continue to make iterations on the design firsthand personally motivated them to contribute to improving the system.

There wasn't any significant power imbalance between our team and Efe or Alex, they treated us as peers and teammates and responded very well to our ideas. Efe made it very clear from the start that he was here to support us, and was not interested in dictating design decisions. Alex was also very supportive. He was available for anything we asked for but not imposing his opinions or forcing any decisions.

There weren't many ethical dilemmas we faced during the semester, but there were a few red tape hurdles that we handled. Humanetics is very protective of their intellectual property (IP), and they were unwilling to share any of their engineering documentation. We overcame this obstacle with the help of Miranda, who also works at UMTRI. She used a handheld 3D scanner to create a model of the UFOnano to base our CAD on. Another hurdle was the uncertainty surrounding what we could and couldn't do in terms of robot modification. Alex helped where he could but if we had wanted to modify the robot in a significant way we would've needed to ensure compliance with the insurance policy and a Humanetics worker would need to approve the changes. We overcame this by utilizing the existing magnet holes in the UFOnano in our design.

If our product were to enter the marketplace, there is a somewhat significant uncertainty in how our IP would be handled and how our team would work with Humanetics. The only way we can foresee our design making it to market would be in collaboration with Humanetics, and it's unclear whether there would be a new patent, if they would request access to our IP, if they would want to purchase the rights to our IP, or something else entirely.

Recommendations

We first recommend continuing testing on the requirements we were not able to fully verify, such as our durability and wind speed requirements. Ensuring that the design remains reliable under many impact cycles as well as wind is imperative for ensuring efficient testing. Other rain corrosion protection coatings

can be sprayed on the parts to avoid oxidation from rain and moisture as well. Avoiding corrosion of any kind is essential for parts that will be used for many cycles.

We recommend adding the foam to the bottom of the battery plate to dampen the vibrations of the batteries inside the robot. Because these batteries cost tens of thousands of dollars, this is a vital addition to avoid the risks that come with worse or damaged batteries.

We also recommend that the magnetic retention design could be modified if the retention force is inadequate. The current design has holes for the magnets and tapped holes for fasteners that secure the magnets to the front and back plates under loading. Our average magnetic retention forces are 52N for magnets that we bought from McMaster listed with 80N forces. Because the stronger magnets on McMaster have larger outer diameters, the 0.75” diameter magnetic holes can be slightly enlarged from additional CNC milling (if necessary) to fit them. The tapped hole can be unmodified or enlarged as well based on the inner hole diameter.

As mentioned, one of our biggest concerns about our design is its ability to succeed in not only harsh environmental conditions but other testing conditions like potholes, angled surfaces, and vibration. We believe generating additional requirements allotting to these issues would be of great use to Mcity. Further, we recommend that Mcity conducts verification testing for these requirements as that would help provide Mcity, stakeholders, and car OEMs detailed data on the design’s performance across more testing conditions, which would ultimately help advance autonomous vehicle research and safety.

Conclusions

Since the start of the semester, our team has moved from initial problem definition and context to concept studies to the development, analysis, and verification of our final mounting system design for the UFOnano robotic carrier. The previous mounting system failed because the magnetic retention force was insufficient, and therefore the dummy detached prematurely from the mounting system during rapid acceleration and deceleration events. In order to address these issues, we have developed an updated mounting system with two additional magnet mounting locations (at the front and rear) of the UFOnano, utilizing a machined mounting block and modified battery cover, while retaining the same mounting interface and geometric constraints as the previous mounting system. This update increased the total available magnetic retention force and improved load distribution, thereby reducing localized stresses in the mounting system and minimizing rotational motion of the dummy during operation. It also increased the required tension in the tethers to detach the magnets, which was crucial to ensure the dummy does not prematurely release from the robot.

Based upon a weighted Pugh matrix and a Failure Modes and Effects Analysis (FMEA), we selected magnet-based solutions to provide the highest reliability, lowest failure risk, and best compliance with project requirements relative to latch-based and/or spring-based solutions. A primary advantage of permanent magnets is their use as a passive retention method with no moving parts; which results in increased durability, reduced mechanical complexity, and ensures reliable detachment during vehicle impact, without jeopardizing the integrity of the robot or test vehicle.

In addition, preliminary force analysis indicated that the current magnet configuration would be inadequate to support the required acceleration levels; thus providing evidence that additional magnets and optimization of the tether geometry were needed. By adding new magnet locations and optimizing magnet orientation we anticipated that the maximum allowable acceleration prior to detachment would be achieved, while maintaining a controlled release of the system during vehicle impact. We performed verification testing for almost all of our requirements, and were able to easily meet our permissibility, simple, reliable (only lateral acceleration and deceleration), impact conditions, cheap, overrunnable, and realistic requirements. Based on our force analysis and verification results, we are confident that the design will meet the remaining requirements during UFOnano operation, while also safely detaching when exposed to vehicle impact forces.

We consider our final design to represent a significant improvement over the existing mounting system and establish a tunable and scalable framework for optimizing the retention force through magnet selection, placement, and configuration. Future effort will include verifying the final requirements, administering validation surveys to Alex and Jim, and possibly creating new requirements for other testing conditions like vibration, uneven terrain, and potholes. Ultimately, these future efforts will result in a final mounting system that meets all engineering specifications, improves test efficiency at Mcity, and provides a reliable, durable, and safe mounting solution for the testing of autonomous vehicles.

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Appendix A: Concepts

Magnetic

1. Add more magnets to increase the securement force applied, decreasing the likelihood of premature detachment.
2. Change the magnets to stronger magnets to increase the securement force applied, decreasing the likelihood of premature detachment.
3. Adjust the geometric arrangement of the magnets to see if the securement force applied increases, decreasing the likelihood of premature detachment.
4. Use electromagnets instead of traditional magnets, which would enable switching the magnets on and off. This would allow the magnetic force to be much stronger during the acceleration of the robot, since the magnetic force turns off prior to impact with a vehicle.
5. Use quantum levitation with superconductors cooled below their critical temperature, allowing contactless securement.
6. Move the magnets off center to see how the securement force changes.
7. Use magnets that naturally get weaker as a vehicle approaches. (unclear if this is physically possible.)
8. Equip the car with a machine that sends some sort of electromagnetic pulse, temporarily deactivating the magnets securing the dummy to the robot. (unclear if this is physically possible.)
9. Add tethers with magnets to the sides of the robot for added stability.
10. Make the battery cover magnetic so more magnets can be used in that space on the robot.

Mechanical

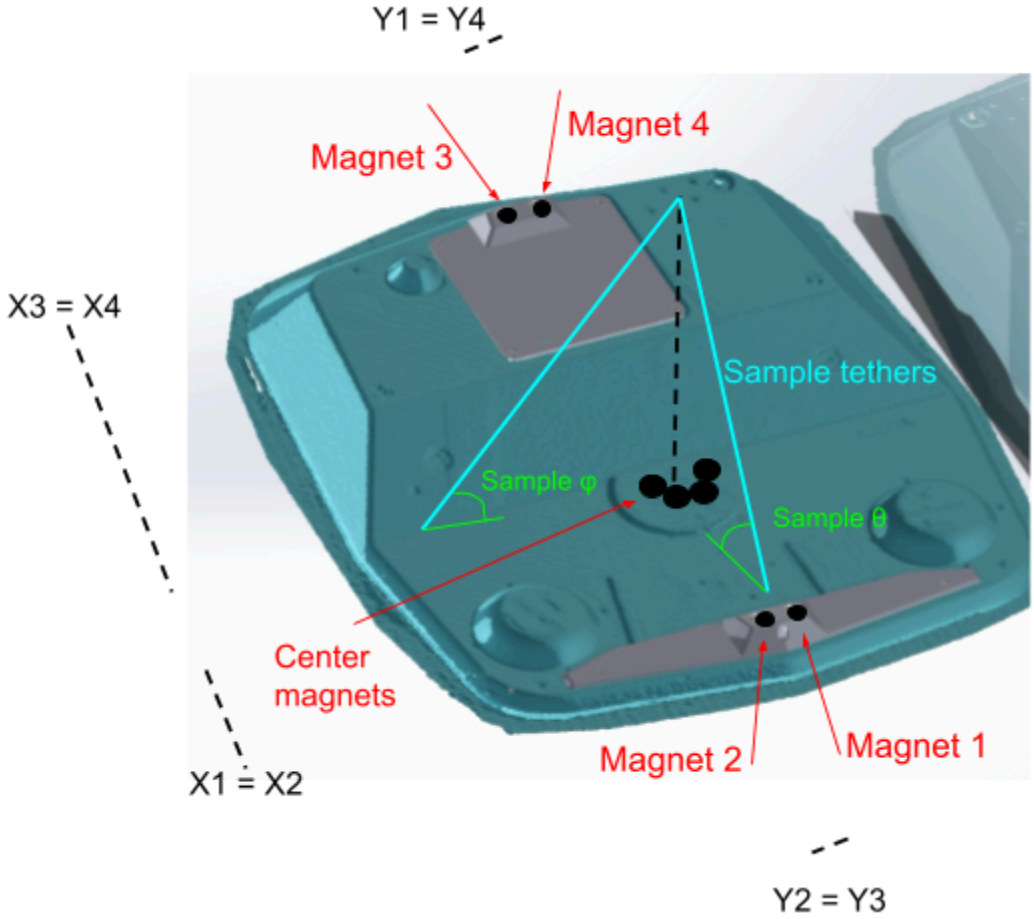
1. Make the dummy post a telescoping post that retracts into the robot at the right time.
2. Secure the dummy with springs to increase the securement force, decreasing the likelihood of premature detachment.
3. Implement a clear horizontal pole to enable tethers in all four cardinal directions.
4. Make a splitter so one hole in the baseplate can have two tethers attached, increasing the securement force.
5. Use a spring based center mount that is adjustable to release at different force applications.
6. Change the tether material to be more elastic, potentially storing some energy and reducing risk of premature detachment.
7. Implement a jerk dependent latch that requires a strong jerk to release, like the dummy experiences when struck by the vehicle.
8. Use an adhesive with high stiffness but can shear off upon impact by the vehicle.
9. Use a breakaway fastener that holds during acceleration and breaks upon vehicle impact.
10. Use a 3D printed with holes for more magnets and press fit into existing baseplate holes.
11. Use a latch and lock mechanism that unlatches after a certain amount of force is applied.
12. Add an extension spring to the tether to resist deflection.
13. Manipulate the angle of the tether to change the force applied to the dummy.
14. Use manual release pins that are removed by pulling a rope at a certain time.
15. Move the center of mass of the dummy to change the force required for detachment.
16. Equip the dummy with a jetpack, allowing maximal detachability.

17. Make the dummy's legs functional, eliminating the need for the robot entirely.
18. Attach the tether's lower on the dummy, changing the forces experienced by the dummy.
19. Tethers detach upon impact, increasing detachability.
20. Equip the dummy with clear wings, eliminating the need for the robot entirely.
21. Turn the dummy into an RC plane, eliminating the need for the robot entirely.

Smart

1. Secure the dummy with a pin, then when the vehicle is close enough to the dummy a signal is sent for the pin to release.
2. Secure the dummy with a latch, then when the vehicle is close enough to the dummy a signal is sent for the latch to release.
3. Use a MOSFET or other electrical system to manipulate the magnet's strength at desirable times.

Appendix B: Detailed Force Analysis



Point we take moments at is (0.753, 1.032) (m) in solidworks (x,y)
Magnet front 1 is (0.514, 1,011) (m)
Magnet front 2 is (0.514, 1,052) (m)
(Tethers 1,2)

Magnet back 3 is (1.157, 1.011) (m)

Manget back 4 is (1.157, 1.052) (m)
(Tethers 3,4)

Moment Arm Lengths

X1	X2	X3	X4
0.239m	0.239m	0.404m	0.404m

Y1	Y2	Y3	Y4
0.021m	0.021m	0.021m	0.021m

Θ angles of tethers 3, 4 is 81.9 deg
Θ angles of tethers 1, 2 is 80.5 deg

Moment empirically determined from force applied at middle magnet location/pole inserting to base plate is 2kg * 0.9m = 1.8kgm = 17.7Nm.

Wind Force

We modeled wind as a drag force acting on the dummy. In fluids, dynamic pressure (q) is 0.5(rho)(V^2).
Wind force = 0.5(rho)(Cd)(A)(V^2) = qCdA.
Air density rho = 1.225kg/m^3 at sea level.

- We assume the drag coefficient C_D for humans is 1.1 - taken from the internet.

For an average height adult, assume frontal area is 0.6m/s^2, side area is 0.3m/s^2 and 45 degree area is (0.6 + 0.3)/(sqrt 2) = 0.63m/s^2.

Front: q = 0.5(1.225)(25) = 15.3N/m^2 and F_{wind} = q*1.1*0.6 = 10.1N
Side: q = 0.5(1.225)(25) = 15.3N/m^2 and F_{wind} = q*1.1*0.3 = 5.1N
45 degree q = 0.5(1.225)(25) = 15.3N/m^2 and F_{wind} = q*1.1*0.63 = 10.6N

- Applied at the center of pressure, but we are initially assuming it is at the center of gravity.

Forward Acceleration:

When it accelerates at a = 3m/s^2, inertia force is Md*a (only dummy mass) backward
Horizontal force balance: (T1costheta1 + T2costheta2) - Ff = Md*a+Fwind

- Tethers and friction oppose force

Vertical: normal force -T1sintheta1 - T2sintheta2 - T3sintheta3 - T4sintheta4= Md*g + Fmbottom
Moment:
Inertia moment = Md*a*h
Worst case total moment = (Md*a+Fwind)*h

- Moment resisted by tethers and moment at 4 magnets at center
- The tethers only provide force if in tension, otherwise they will slack and not provide any force

Moment sum at bottom magnets:
(Md*a+Fwind)*h =∑Tisin(thetai)xi + 17.7Nm for T>0

- xi is horizontal distance from tether to bottom magnets
- Assume E for each rope is same

Magnets 1, 2 provide (T1)sintheta*(x1)+ (T2)sintheta*(x2) moment
(Md*a+Fwind)*h = (T1)sintheta*(x1)+ (T2)sintheta*(x2)+ 17.7Nm

Add 1.3 safety factor
1.3((6.5kg*a + 10.1)*0.99m) = (T1+T2)(0.239m)*sin(80.5) + 17.7Nm

If tethers experience same tension (which they will since same length and E), 1.3(6.435a+10) = 2T(.986)(.239) = 0.471T + 17.7Nm
At 3m/s^2 acceleration, need 43N force magnet pull with safety factor of 1.3

Backward Acceleration:
(Md*a+Fwind)*h = (T4)sintheta*(x4)+ (T3)sintheta*(x3) + 17.7Nm
6.435a+10 = 2Tsin(81.9)(.404) = .8T + 17.7Nm
Add 1.3 safety factor
At 3m/s^2 acceleration, need 26N force magnet pull with safety factor of 1.3

Rightwards Acceleration:
φ for tethers 1 and 2 is 86 degrees
φ for tethers 3 and 4 is 86 degrees

(Md*a+Fwind)*h = ∑Tisin(phi)yi + 17.7Nm
(Md*a+Fwind)*h = T2sin(86)(y2) + T3sin(86)(y3) + 17.7Nm
6.435a+5.1 = T2sin(86)(.021) + T3sin(86)(.021) + 17.7Nm
Add 1.3 safety factor
At 1.5m/s^2 acceleration, 19.2 = .021T2 + .021T3 + 17.7Nm
At 1.5m/s^2 acceleration, need 36N force magnet pull with safety factor of 1.3

Leftwards Acceleration:
(Md*a+Fwind)*h = ∑Tisin(phi)yi+ 17.7Nm
(Md*a+Fwind)*h = T1sin(86)(y1) + T4sin(86)(y4)+ 17.7Nm
6.435a+5.1 = T1sin(86)(.021) + T4sin(86)(.021)+ 17.7Nm
Add 1.3 safety factor
At 1.5m/s^2 acceleration, 19.2 =.021T1 + .021T4+ 17.7Nm
At 1.5m/s^2 acceleration, need 36N force magnet pull with safety factor of 1.3

Final Conclusion:
Minimum magnet pull force is 43N

100N Detachment:
Moment applied at same location due to 100N force at center of gravity
= 100N*0.99m = 99Nm

Maximum longitudinal moment provided by our 52N design for forward acceleration
= 17.7Nm + 0.471T = 42.2Nm
Maximum longitudinal moment provided by our design for backward acceleration
= 17.7Nm + 0.8T = 59.3Nm
Maximum longitudinal moment provided by our design for lateral acceleration
= 17.7Nm + 0.042T = 19.9Nm
All within our 100N requirement.

Appendix C: Verification and Validation Traceability Log

Verification Matrix

Spec ID	Specification	Test Condition	Instrumentation	Measured Variable	Acceptance Threshold	# Trials	Rationale
REL-01	Withstands 3 m/s² longitudinal acceleration	UFONano operated at 3 m/s² forward and backward acceleration with mounted dummy	UFONano control system, visual observation, video recording	Attachment status (detach/no detach)	Dummy remains attached in ≥19/20 trials per direction (≥95%)	20 forward, 20 backward	Ensures statistical confidence for the most critical operational load (primary failure mode = premature detachment)
REL-02	Withstands 1.5 m/s² lateral acceleration	UFONano operated at 1.5 m/s² lateral motion (left/right)	UFONano system, visual observation, video	Attachment status	≥19/20 successful trials per direction	20 left, 20 right	Lateral loading introduces different moment arms and rotational effects, so equivalent testing rigor is required to capture worst-case conditions
REL-03	Withstands wind up to 5 m/s	Expose system to airflow up to 5 m/s at 0°, 90°, 180° relative to motion (with and without robot movement)	Anemometer, visual observation, video	Attachment status	≥9/10 successful trials per orientation	10 per direction	Wind direction affects force magnitude and moment location so multiple orientations are required to capture realistic aerodynamic loading
IC-01	Dummy detaches when 100 N are experienced	Apply controlled force at about 2.5 ft height using force gauge in X, Y, and 45° directions	Calibrated force gauge/strain gauge setup	Detachment force (N)	Dummy detaches at/before 100 N in all trials	5 per direction (15 total)	Expands testing procedures to off-axis loading to address shear/peel effects identified in FBD

IC-02	Dummy detaches in all impact cases	Controlled vehicle impact test with dummy mounted	Vehicle test setup, visual observation, video, inspection	Detachment occurrence, system damage	Dummy detaches in all trials with no damage to robot/vehicle	5 trials	Highest-level functional verification; ensures real-world functionality
OVBL-01	All rigid components remain within 20–65 mm profile	Measure fully assembled system on UFONano	Calipers	Height above baseplate (mm)	All components within 20–65 mm envelope	3 per component	Low variability measurement; multiple readings ensure accuracy without excessive testing
DUR-01	System withstands repeated use	Apply 2× detachment force repeatedly	Force setup, visual inspection tools	Structural condition, functionality	No cracks >5 mm, no deformation, no loosening	100 cycles	Accelerated life testing allows characterization of long-term degradation effects

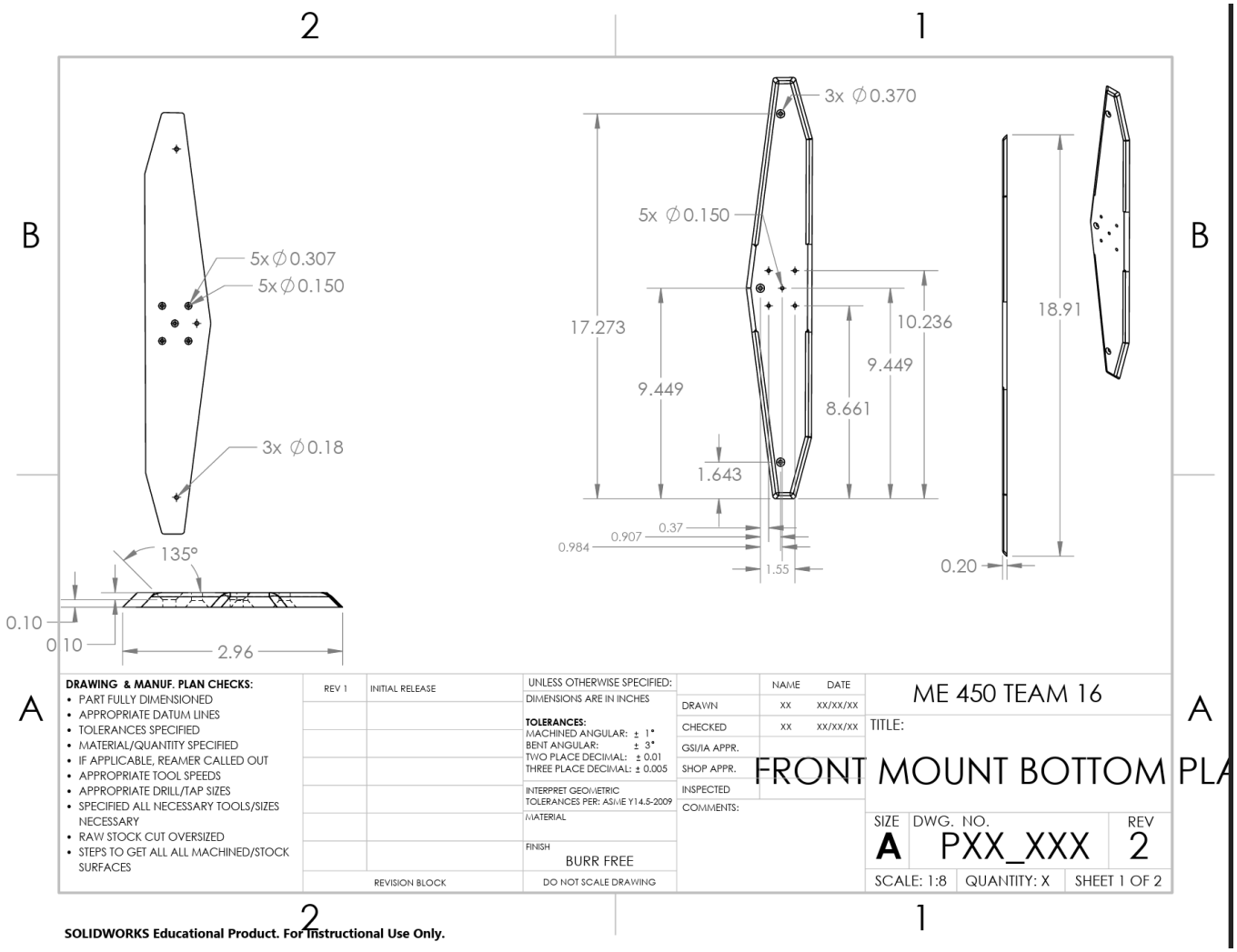
Validation Matrix

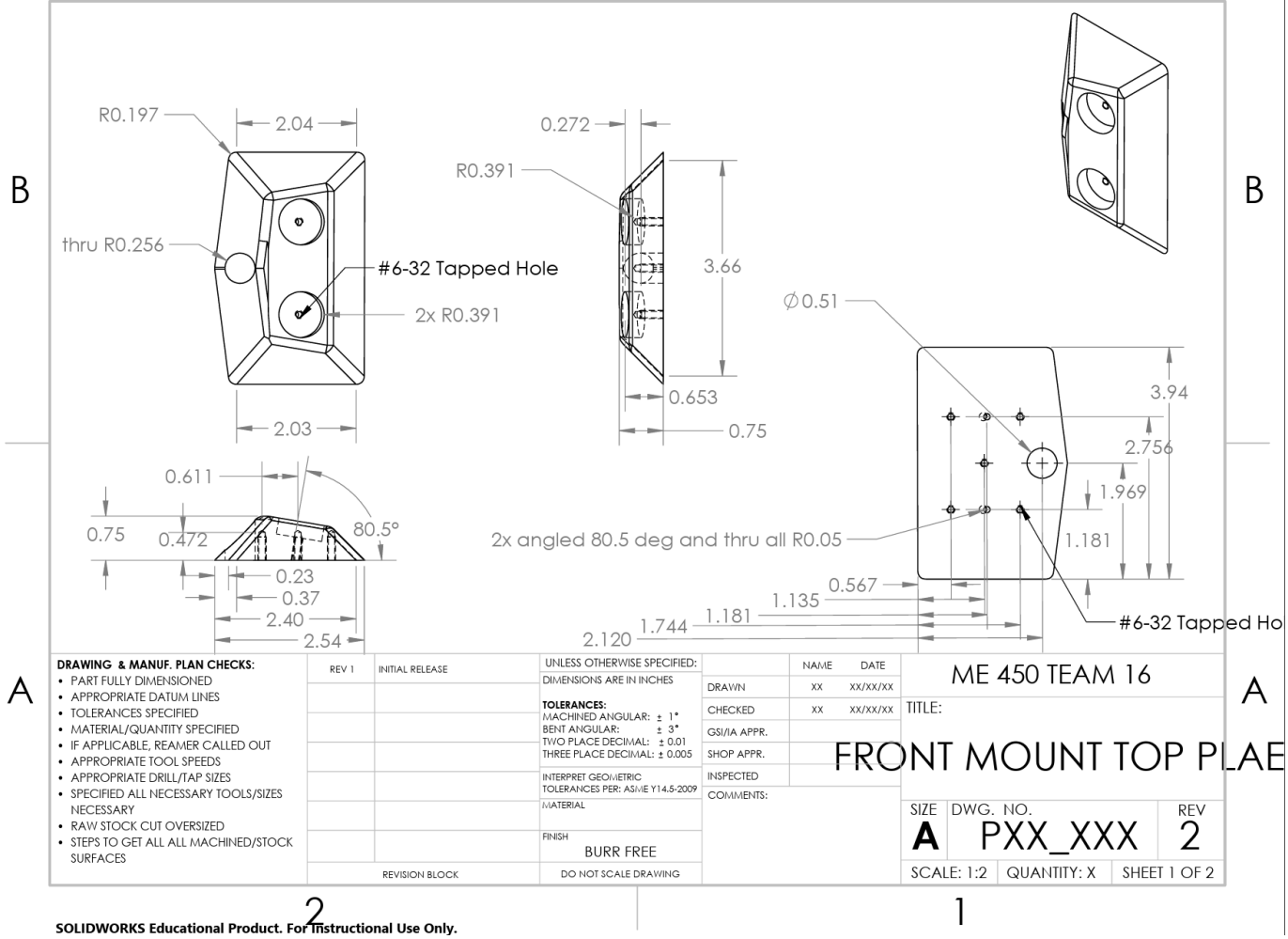
Validation ID	Requirement	Validation Scenario	Instrumentation / Evidence	Measured Variable	Success Criteria	# Trials	Rationale
DET-VAL-01	Detachment Performance	Realistic vehicle interaction testing	Observation, video, post-test inspection	Detachment behavior, damage	Dummy detaches safely and consistently with no damage	5 trials	Directly validates primary design goal in real-world conditions
REL-VAL-01	Operational Reliability	UFONano operates under realistic acceleration and environmental conditions	Observation, video	Premature detachment occurrence	No premature detachment during operation	5 runs per condition	Complements verification by testing full-system behavior rather than isolated conditions; better indication of real-world performance
OVBL-VAL-01	Overrunnability	Vehicle interaction with mounted system	Observation, inspection	Interference with vehicle interaction	No interference; maintains low-profile behavior	3–5 trials	Ensures geometric compliance translates to real-world usability and minimal interaction interference
USER-VAL-01	Usability (Operators)	Operator performs mounting and testing procedure	Observation, feedback collection	Ease of use, setup time	One-person operation, no tools, <2 min setup	3–5 operators	Confirms stakeholder usability requirements
DUR-VAL-01	Durability	Repeated real-world testing cycles	Observation over time	Performance consistency	System maintains performance over repeated use	Multiple cycles	Validates long-term functionality beyond controlled lab conditions

Appendix D: Build Design Bill of Materials

Part name	McMaster-Carr Part Number	Location(s)	Quantity	Cost per unit ($)	Total cost ($)
Front Plate Bottom 1/5" alum. plate (20" x 3")	89015K33		0.5	118.11	59.06
Front Plate Top aluminum block (100mm x 65mm x 20mm)	9246K576		0.5	0 (used from shop)	0
Battery Plate Bottom 1/5" alum. plate (12"x12")	89015K33		0.5	118.11	59.06
Battery Plate Top aluminum block (100mm x 100mm x 20mm)	9246K576		0.5	0 (used from shop)	0
Magnet	5862K925	Front and ack	4	9.38	37.52
Screw 1	92210A148	New magnets, front and rear connections	1	5.79	5.79
Screw 2	90236A135	Old magnet holes	1	10.69	10.69
Screw 3	90236A133	Corners of battery	1	4.8	4.8
Tether	97840A680		1	33.15	33.15
Tether magnet 3/4" x 12" cylinder stainless steel stock	89535K12	Steel end that connects to magnets	1	17.55	17.55
New magnets (stronger)	5862K228		4	8.56	34.24
First magnet (one broke)	5862K925		1	9.38	9.38
Tether from REI	Bought from REI	Tethers that connect magnets to dummy	1	6.89	6.89
Plain Carbon Steel	Bought from Lowe's	Steel end that connects to magnets	1	19.02	19.02
Total Sum					**$297.14**

Appendix E: Engineering Drawings





DRAWING & MANUF. PLAN CHECKS:

- PART FULLY DIMENSIONED
- APPROPRIATE DATUM LINES
- TOLERANCES SPECIFIED
- MATERIAL/QUANTITY SPECIFIED
- IF APPLICABLE, REAMER CALLED OUT
- APPROPRIATE TOOL SPEEDS
- APPROPRIATE DRILL/TAP SIZES
- SPECIFIED ALL NECESSARY TOOLS/SIZES NECESSARY
- RAW STOCK CUT OVERSIZED
- STEPS TO GET ALL ALL MACHINED/STOCK SURFACES

REV	REVISION BLOCK
1	INITIAL RELEASE

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES

TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005

INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009

MATERIAL

FINISH: BURR FREE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	XX	XX/XX/XX
CHECKED	XX	XX/XX/XX
GSI/IA APPR.		
SHOP APPR.		
INSPECTED		

COMMENTS:

ME 450 TEAM 16

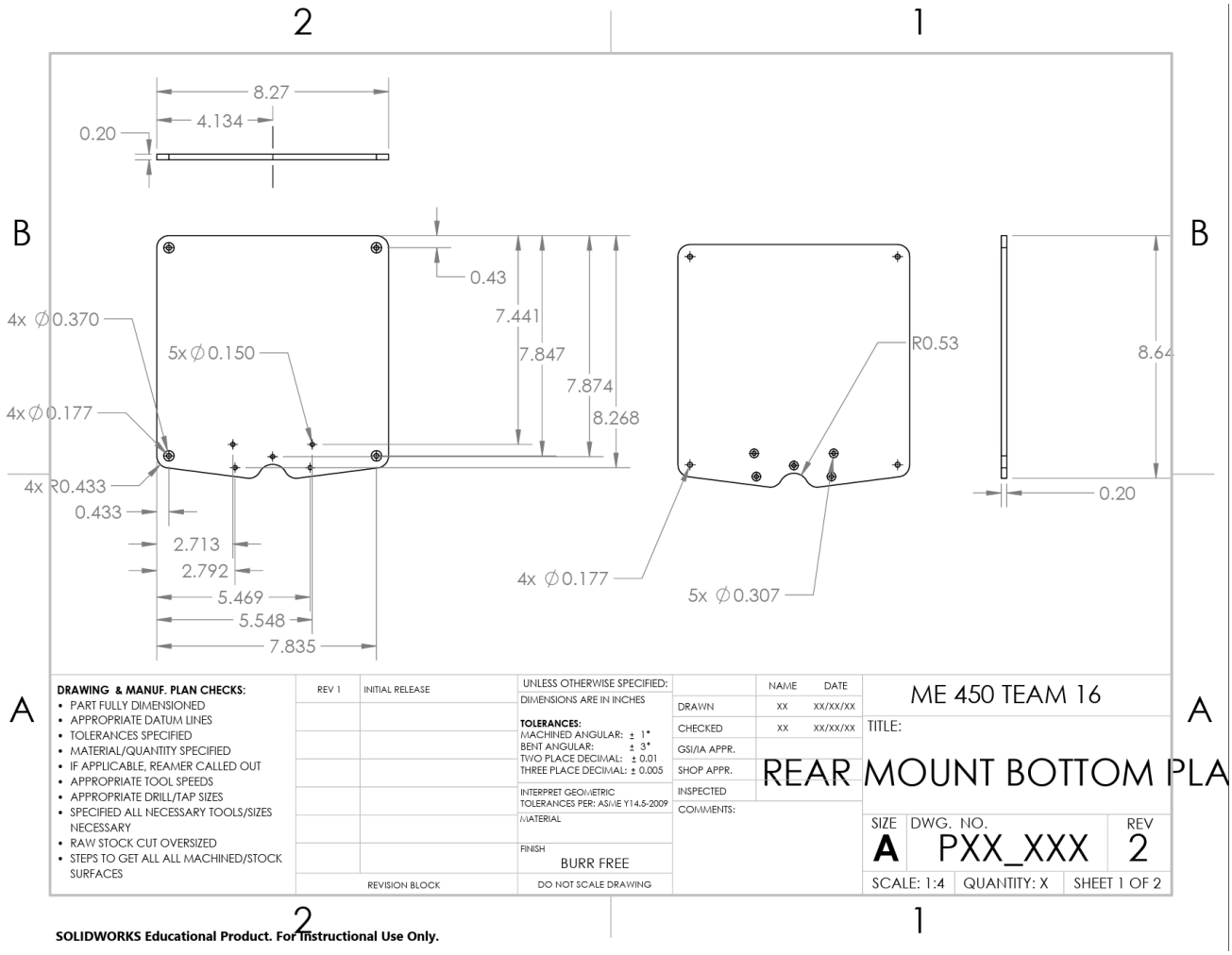
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FRONT MOUNT TOP PLAE

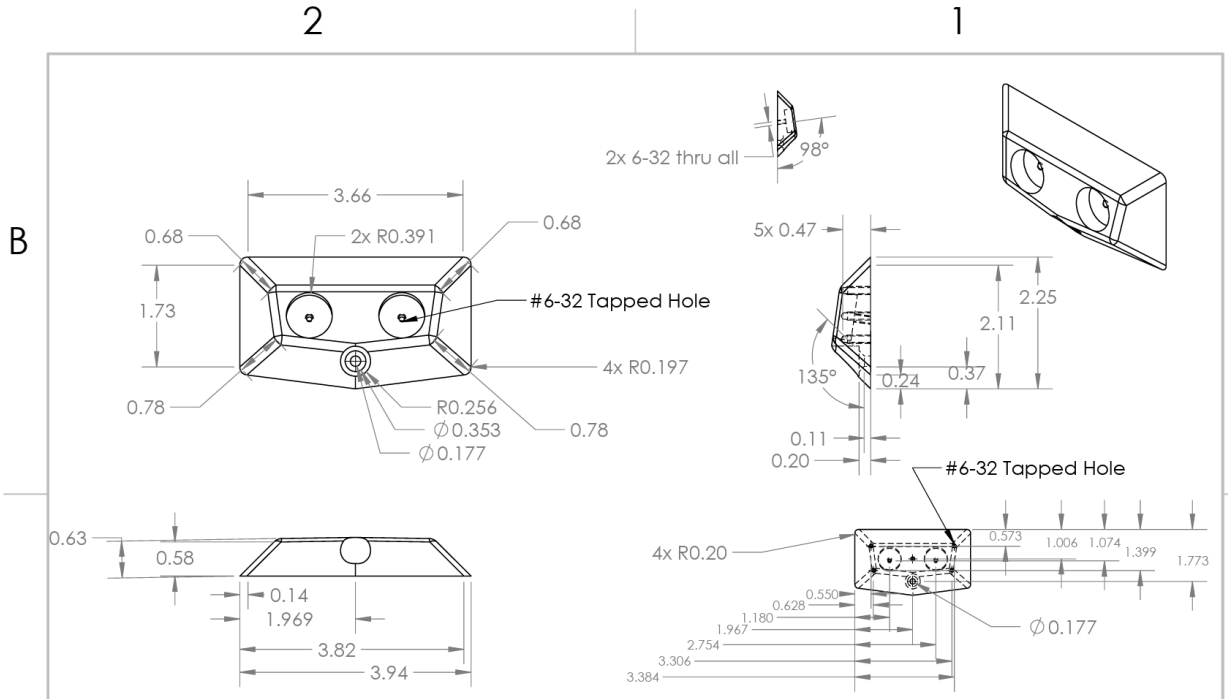
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SCALE: 1:2	QUANTITY: X	SHEET 1 OF 2

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DRAWING & MANUF. PLAN CHECKS:

- PART FULLY DIMENSIONED
- APPROPRIATE DATUM LINES
- TOLERANCES SPECIFIED
- MATERIAL/QUANTITY SPECIFIED
- IF APPLICABLE, REAMER CALLED OUT
- APPROPRIATE TOOL SPEEDS
- APPROPRIATE DRILL/TAP SIZES
- SPECIFIED ALL NECESSARY TOOLS/SIZES NECESSARY
- RAW STOCK CUT OVERSIZED
- STEPS TO GET ALL ALL MACHINED/STOCK SURFACES

REV	REVISION BLOCK
1	INITIAL RELEASE

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

TOLERANCES:
MACHINED ANGULAR: ± 1°
BENT ANGULAR: ± 3°
TWO PLACE DECIMAL: ± 0.01
THREE PLACE DECIMAL: ± 0.005

INTERPRET GEOMETRIC TOLERANCES PER: ASME Y14.5-2009

MATERIAL

FINISH
BURR FREE

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	XX	XX/XX/XX
CHECKED	XX	XX/XX/XX
GSI/IA APPR.		
SHOP APPR.		
INSPECTED		
COMMENTS:		

ME 450 TEAM 16

TITLE:

REAR MOUNT TOP PLATE

SIZE	DWG. NO.	REV
A	PXX_XXX	2

SCALE: 1:4 | QUANTITY: X | SHEET 1 OF 2

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Biographies

My name is Peter Florence and I am a senior Mechanical Engineering student with a minor in Music in my last semester at the University of Michigan. I was born and raised in Ann Arbor, and attended Pioneer High School, which is across the street from the Big House. I've always been fascinated by math and science, and engineering is the perfect fit for me to pursue those interests. I chose mechanical engineering specifically because it's so broad and you can really do whatever you want to do with a mechanical engineering degree. I was a member of the Michigan Marching Band for all four years, and went to the Rose Bowl and the National Championship in my sophomore year, which were my favorite band memories by far. I'm a member of The Initiative, an engineering project team through M-HEAL developing an affordable infant warming bassinet to combat neonate hypothermia deaths in Ghana. I've accepted a full time job upon graduation at IMEG, an engineering consulting firm with an Ann Arbor office based at Domino's Farms. I'm super excited to be able to stay in Ann Arbor and be close to my family, and continue being a part of the Michigan community!

My name is Andrew Spagnuolo and I am in my last semester of Mechanical Engineering at the University of Michigan. This is only my second year studying here, as I transferred in from Arizona State University. I spent a majority of my life in Allen, Texas where I played varsity hockey for Allen High School before graduation. Before this, I played travel hockey for 8 years, winning 5 state championships within. I chose mechanical engineering due to my fascination with cars, figuring out how things work, and exploring ways of product improvement. Through my studies at University of Michigan, I have been a part of the operations board for Michigan Fabrication where I serve as the safety and machine shop leads. I was accepted into the SUGS program at U of M to achieve a masters in mechanical engineering, and before then I have accepted an offer for a product development internship working with internal combustion engines and hybrid vehicle transmission with General Motors this upcoming summer. My long term goal after graduating with my masters degree is to earn a pilot slot in the US Air Force and fly fighter jets. A few of my hobbies outside of school consist of working on cars, mountain biking, wakeboarding, and bouldering.

My name is Amogh Bollapalli, a mechanical engineering student from Novi, Michigan. I have been interested in math and physics since I was very young, and did well in a few math competitions in high school. I chose mechanical engineering because I wanted to use my interests in math, physics, and mechanical engineering principles to help design products that create an impact. I am part of M-AST, which designs, manufactures, and tests hand held quadcopters. We fly them at speeds up to 80 mph in the M-Air net. In my free time, I like to read about math, play quite a bit of video games, and work with a team to administer competitive Pokémon and Bloons tournaments. I will be working at General Motors in Warren, MI doing virtual validation (computer aided engineering analysis) after graduating this semester.

My name is Dale Newman, and I am a senior in Mechanical Engineering here at the University of Michigan. I came here in 2021 after graduating and completing the International Baccalaureate Diploma Program at Miramar High School in South Florida. Growing up, I was always quite passionate about drawing and designs. In addition, I spent the majority of my educational years in advanced classes for math, so after finishing Calc I during my IB Program, I decided that becoming a mechanical engineer would be a good degree decision that would allow me to combine my love for math and designing, while expanding my ability to do work in the aerospace/automotive industry in the future. This summer, I

finished an internship as a Technical Engineer in Greensboro, North Carolina with Procter & Gamble, and I'm currently planning to return there this Fall after graduating. I'm currently the Transmission Sub-team lead of BlueLAB Woven Wind, a project team here at Michigan that is currently developing a wind turbine to put on a Michigan elementary school to teach kids about engineering and reusable energy. Some hobbies of mine also include going to the gym, learning day/swing trading options, watching movies/TV shows (my favorites are Interstellar and The Sopranos), and playing chess.