Quadruped Support System

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Abstract

This report examines the engineering design process to create a mounting system for a quadruped robot dog, such that it can support configurations with either a robotic manipulator arm or a drone landing pad mounted on the robot. The quadruped robot is being used for research by the UIC Robotics and Motion Laboratory, which aims to develop further methods of robotic interaction with the world. The aim of the quadruped support system is to expand the versatility of the robotic dog by allowing it to attach and interact with a wider array of accessories. This report examines relevant similar technologies and design constraints needed to develop a suitable design for the support system, as well as selection of a design from three proposals created. Risk factors for the design and the overall system are analyzed to guide the design process. Following the actual manufacture of the initial prototype, structural analysis and physical testing was performed to guide the process of design modification. This allowed for the development of an improved support system design. Further validation testing of the improved design led to a finalized version that works with the quadruped.

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Introduction

The UIC Robotics and Motion Laboratory has a quadruped research robot, the Unitree A1, that it uses to perform experiments. In order to use this robot for a more diverse set of experiments, a mounting interface must be developed so that a robotic manipulator arm may be attached to the back of the quadruped so that the arm can be used to pick and place objects. Separately, a landing platform and mounting interface for said platform must be developed such that an independent flying drone may land on top of the quadruped and then take off again. Additionally, mounting interfaces for a camera and a graphics processing unit (GPU) must be developed for the quadruped that are compatible with both the landing platform and the manipulator arm.

The sponsor is Professor Pranav Bhounsule of the Department of Industrial and Mechanical Engineering. Our sponsor would like to perform a more diverse set of experiments with a quadrupedal robot involving drones, a robotic manipulator arm, camera and a graphical processing unit. Such experiments could be but not limited to: picking up and carrying of objects of varying sizes, landing a drone while the platform is stationary and dynamic, and improvement of the vision of the robot. These experiments are conducted to solve problems in a number of real life scenarios. Armed forces utilize small multipurpose equipment transports that are able to mount various tools and gadgets on quadruped robots to aid the load for troops. Quadruped robots can also be used to pick up hazardous waste such as radioactive materials or perform other dangerous actions like bomb defusal to save lives. Quadruped robots can also be used in less extreme environments such as obtaining footage for documentaries/recreational videos and maybe one day might be a household companion that can retrieve things for the user.

The quadruped robot is generally designed to traverse dynamic geographical terrains in order to transport or deliver an additional payload or function when physical stability is needed[9]. This means that the robot needs to be able to traverse and perform under potentially difficult terrain in order to produce the desired results without structural or systemic failure. An example of this function is the Anybotics Anybot, which is effective in traversing an industrial[9] and natural setting[10]. The reason is because the quadruped could have a hard time recovering from such failures and any issues that arise within the processes due to failure will often "snowball" as more operations are conducted. Furthermore, it should be noted that the quadruped often has specialized parts and attachments that are meant to operate with. A common part that is often found with the quadruped is an external camera that operates as a "second sense" for the robot [8], which is very important for the robot because its general design is to have a fixed forward-facing camera that allows the robot to determine how it should traverse a terrain while the external camera identifies other obstacles and objectives in the surrounding area. However, due to the specialized nature of the attachments that can come with the robot, the user must work under a number of constraints in order to design their own attachments for the quadruped. Some of these constraints include the effects of a shifted center of gravity from external attachments, the physical limitations from the quadrupeds range of motion, and the maximum payload.

The quadruped robot can perform multiple tasks from moving back and forth, walking to lightly running, and even jumping. The addition to a robotic manipulator arm is to expand its functionality and performance. While the quadruped is a great example of how an autonomous robot can interact with its environment, the manipulator arm provides a significant upgrade to its capabilities in that regard [3]. The robotic arm would enable the ability to pick up objects that can be transported with the locomotion of the quadruped. The setbacks are its weight limits. The total weight of the object combined with the manipulator arm should not exceed the quadruped's total capacity. Additionally the moment generated by the arm picking up an object while extended must be considered when attaching the arm. Exceeding the safe boundary conditions in this case can lead to increasing instability in the quadruped system, and cause mechanical or systemic failure. The arm needs to be placed in an area that can reach equilibrium with and without an item being held by the robotic arm. With the idea of equilibrium, the robotic arm should be placed along the centerline of the quadrupled robot. We can observe a similar approach to the problem we have in the Boston Dynamic's Spot quadruped robot [4,5], which also comes with a manipulator arm attachment. In their case, the arm is placed towards the front of the robot along its centerline. This demonstrates that the arm can be placed anywhere between the ends of the quadruped's "back" along the centerline and the robot can compensate for changes in center-of-gravity. In our case, the sponsor has stated his desire for the arm to be placed towards the back side of the robot.

With the development of quadcopter drones, a designated landing area is often needed for safe landing and takeoff. Landing pads for drones are commonly inspired by the current system in place for helicopters with the landing area being a larger surface area than the footprint of the rotors, in order for the pad to be able to generate enough lift for takeoff, as well as for safety in landing. In a patent for a drone delivery system one creative approach for the landing area was to have an adjustable landing pad that extends or contracts into the desired area of choice [1]. Furthermore, another approach that could be utilized is in the patent for a helicopter landing pad which features a foldable landing pad which allows for a designated landing position that will reduce the ability for the helicopter/drone to slide off [2]. These are a few examples of many creative approaches that could be implemented into the system for a quadruped robot and quadcopter drone with some slight modifications. The patents are not an exact solution to the problem we are trying to address but are systems similar to what is being performed here. Similar to the manipulator arm, the main constraint here will be the combined weight of the landing pad and drone needing to be lower than the safe limit for the quadruped. Our system will undergo testing not only while the quadruped robot is stationary, but also while the robot is in motion so current models are not sufficient for the problem at hand.

The mounting interface that will be used on this quadruped robot will be paramount in designing the support system. Within the design criteria, the robot is required to accommodate a robotic arm, a landing pad for a drone, cameras, and other essential equipment. Researching existing mounting interfaces can help us determine how we will want to design ours. There are different mounting interfaces that we found upon our initial search. The first is a pegboard. The benefits of a system similar to a pegboard would allow many different placement configurations for the attachments. Pegboards are used in various applications for commercial use. One is that of tool storage. A drawback of this is that pegboards are mostly used to hold items in a stationary position. For this project, the robot will be in motion and the items could therefore be dislodged. Pegboards come in different designs. An example of this can be seen in the figure below. In a patent

filed in 2003 by Eye Designs LLC [6], the pegboard has an ornamental design that would help secure the objects. Another drawback of pegboards would be weight. Since the design criteria for the support system states that its weight should be 10% of the weight of the robot, this will most likely not be viable. A different mounting interface that was researched were conflat flanges. These mounting interfaces are typically made out of steel and do not offer as many configurations as pegboards. They will, however, offer more support than pegboards. An image of this is shown in Figure 2 [7]. There are other applications that can be used as an inspiration for designing our own mounting interface. In helicopters, a device called the swash plate allows the helicopter blades to freely rotate and receive inputs from the pilot. A similar concept can be used for the robotic arm so that it can rotate.

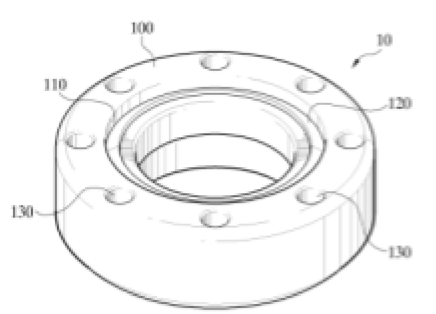

Figure 2. UHV Conflat Flange with Special Knife Edge Seal.

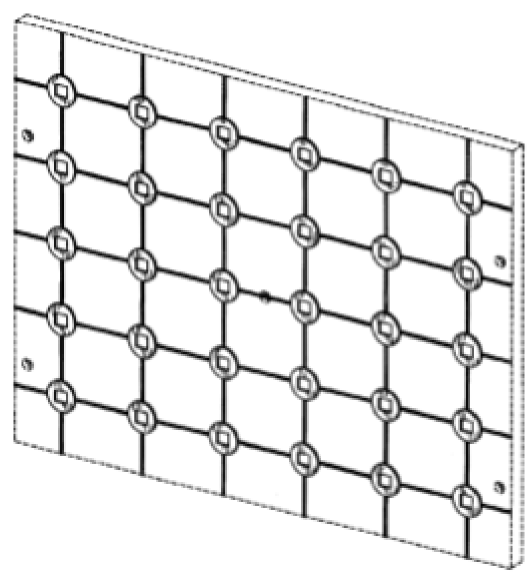

Figure 1. Pegboard design by Eye Designs LLC.

There are a number of design criteria constraints for the quadruped support system. The robotic manipulator arms must be affixed along the lengthwise centerline to ensure that the robot is not off balance. Additionally the total load that the quadruped robot can withstand without failure is 5 kg, but our sponsor has asked us to remain under 3 kg to allow the manipulator arm to lift objects of varying weight without causing damage to the robot or the support system. This load includes the manipulator arm/drone, two controllers, landing platform, and a camera. The controllers are to be used in tandem with the drone for testing purposes regarding landing and will need to be on the robot at all times. A final constraint is that the landing platform must be above the mounted camera at all times. A few key notes from the sponsor to consider is that either the arm or the drone will operate with the robot but not both at the same time. These experiments will be independent from each other. The landing platform is desired to be large enough for easier takeoff and landing of the drone. And finally that the placement of the arm base must be offset to the edges of the robot.

Codes and standards are an important aspect for design in engineering. Without these codes and standards the consumer will not have an assurance of a safe product. There are three standards that we would like to use for our project. The first standard is the IEEE standard for drone applications which establishes a support framework for drone applications. It specifies drone application classes, application scenarios, and required application execution environments. Another standard is the ASME standard for dimensioning and tolerancing. It establishes symbols, rules, definitions, requirements, defaults, and recommended practices for stating and interpreting geometric dimensioning and tolerancing. This will be needed to ensure the design meets the customer requirements and will be easily manufacturable. And lastly, the final code will be the ASTM standard for Specification For Vertiport Design. This specification defines the requirements for the planning, design, and establishment of vertiports intended to service vertical takeoff and landing (VTOL) aircraft. This standard only applies to aircraft of at least 55 lbs, but there are certain aspects that can be used for our design of a landing pad with a drone.

Technical Content

For the purpose of developing a functional mounting system for the quadruped, a few key assumptions must be stated to inform the design. First, the robot is expected to eventually fall and the mounting system to fail as a result. This means that the design should be easy to manufacture and reproduce in the event a replacement is needed. Cheaper materials and a design with a limited number of parts would be useful in this case. Second, the robot is expected to engage in locomotion while the mounting system is attached. This means that the design must be strong enough to withstand a wide range of movements possible from the quadruped without failing due to normal movement of the robot. However, as noted above, the mounting system is not expected to withstand the forces associated with the robot falling over entirely. Third, the robot is expected to use the manipulator arm to pick up objects of varying weight while attached to the mounting system. This means that the weight of the whole system must be low enough under the limit to allow the addition of more weight via the arm picking up something. It also means that the mounting system must be strong enough to withstand the forces associated with the out-stretched arm lifting and carrying a mass. Finally, there will always be various extra attachments, such as a camera and a GPU, attached directly to the back of the robot. These must be accounted for when designing the mounting system, such that the mounting system must be raised from the back of the robot to allow clearance for these attachments.

There are five key metrics that must be evaluated at all stages of the design process to keep within the constraints put forward by the sponsor. These metrics include the weight, cost, yield strength, number of parts, and size.

The weight of the product as a metric is important because the quadruped robot has a maximum load constraint that limits the load that the product can subject to the robot. The sponsor has also stated that the robot will have an arm that will be interacting with other objects and loads, and thus needs the product to be well under this constraint. And so, it should be assumed that the load of the product should include the weight of the drone, the manipulator arm, the external camera, the two controllers, and the weight of the product itself.

The cost of the product is extremely important as the sponsor expects that certain aspects of the product will require repair/replacement at several points in the future. Furthermore, it could also be expected that the design of the product may require modifications in the future and must be easy to modify with minimal effort, time, and monetary cost, as the integrated components or specifications that the product must operate with may change.

The product must have a large yield strength as the sponsor has specified that due to the robots' proclivity to operational failure. To clarify, the quadruped robot will often impact obstacles, fall over due to unforeseen environmental conditions, and will be operating in dynamic mission settings, and so needs to be able to withstand these conditions without sustaining permanent damage or deformation.

The number of parts is important because it can affect the previously stated metrics negatively and positively. The benefits from having a greater number of parts making up the product could allow for the sponsor to more easily salvage and replace certain components, and at a lesser cost, should they get damaged. However, the weight generated by having more parts and from the means at which the parts are affixed together (screws and bolts, adhesives, pins, etc.). Additionally, the sponsor has asked that the product must be easy to repair and detach from the quadruped robot, and having more parts could make this constraint either much more difficult or easy to fulfill.

Finally, there are the geometric constraints that must be accounted for. This metric has several constraints that must be fulfilled, some of which include that there must be enough space on the platform for the drone to land, must allow the limbs of the quadruped to move unimpeded, enough room for a user to interact with the ports on the top face of the robot's body, and must allow for the platform to rise above the additional camera mounted to the top of the robot. All these must be fulfilled because the robot must be able to move unimpeded, with the external camera, and allow the drone to land with some wiggle room. Furthermore, the user must be able to interact with the ports in order to easily make modifications and changes to the systematic set-up.

Proposed Solutions

➢ **Design 1**

Our first proposed design involves a simple rectangular box frame with a set of 8 flanges at the base where the frame would be attached to the quadruped's back by a series of screws. The frame would have a series of holes for screws at the corners of both sides and the top that would allow properly sized pegboards to mount to on each of those three surfaces, as seen below. This would allow the pegboards to be removable and replaceable. It is likely that pre-made pegboards could be purchased and fit to the design as needed, otherwise they would need to be manufactured in-house. The frame itself is 5 inches tall which would allow for the necessary clearance for the back-mounted attachments. The pegboard design for the top is thicker and sturdier to support the larger attachments such as the manipulator arm and the drone landing pad, which would be screwed on to attach. The frame is left open at the front and the back to allow for access to its interior/underside, but could be trivially redesigned to allow for additional pegboards on those sides as well if needed. Additionally, if this design provides inadequate space for the camera to be attached to the robot's back, the frame could be redesigned to remove the lower cross-beam at the front to make room for the camera attachment.

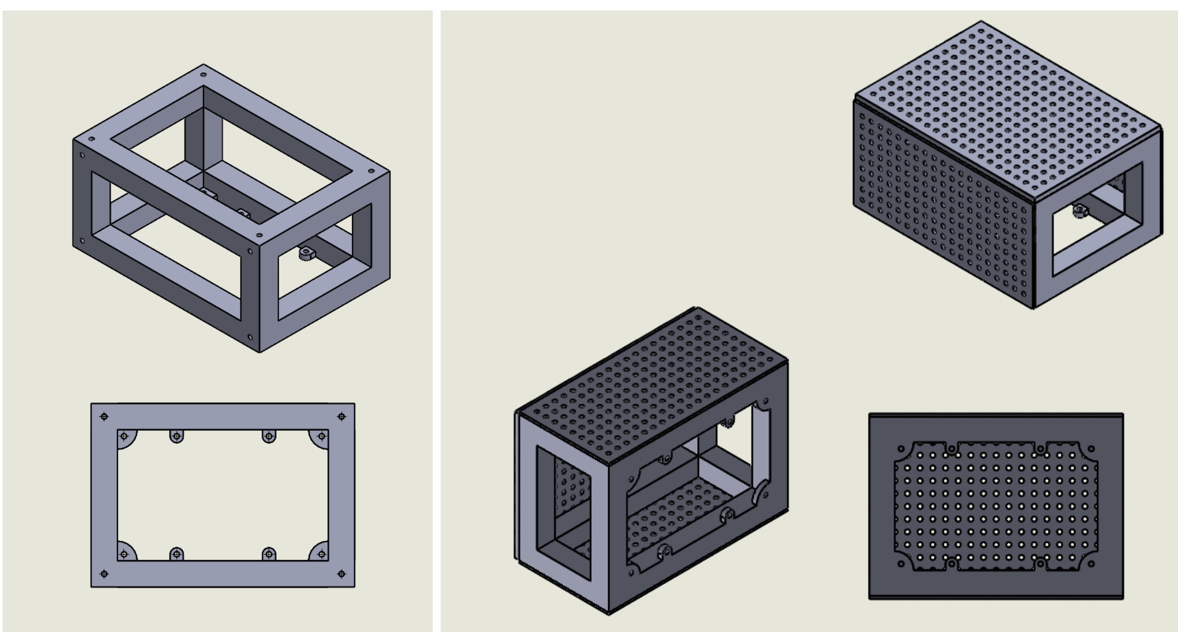

Figure 3. Orthographic and Isometric views of initial design 1 showcasing a minimalistic design and modularity.

➢ **Design 2**

The second proposal design was a platform-and-support system that uses two truss-like elevations as supports that would screw into the quadruped robot at its frontmost and backmost screw holes and would screw into the platform via four screws and nuts holding the three parts together. Additionally the platform would also hang two U-shape containers that would hold the controllers in place in the same fashion. The platform would have slots running along several portions of the design so that the base of the robotic arm would be able to be affixed to the top of the platform at any position that the user would desire to a high degree of specificity. Furthermore, the platform could be made from laser-cut acrylic plastic as the ability to see through the platform to see the ports and analogs along the robot produces a practical and replaceable but light-weight and viable design choice. The controller containers can be made out of 3D printed plastic and allow for free access to the controllers for on-the-bot modification. The supports can also be made of a 3D printed plastic and its design allows for the user to be able to interact with the analog ports on the top of the quadruped robot.

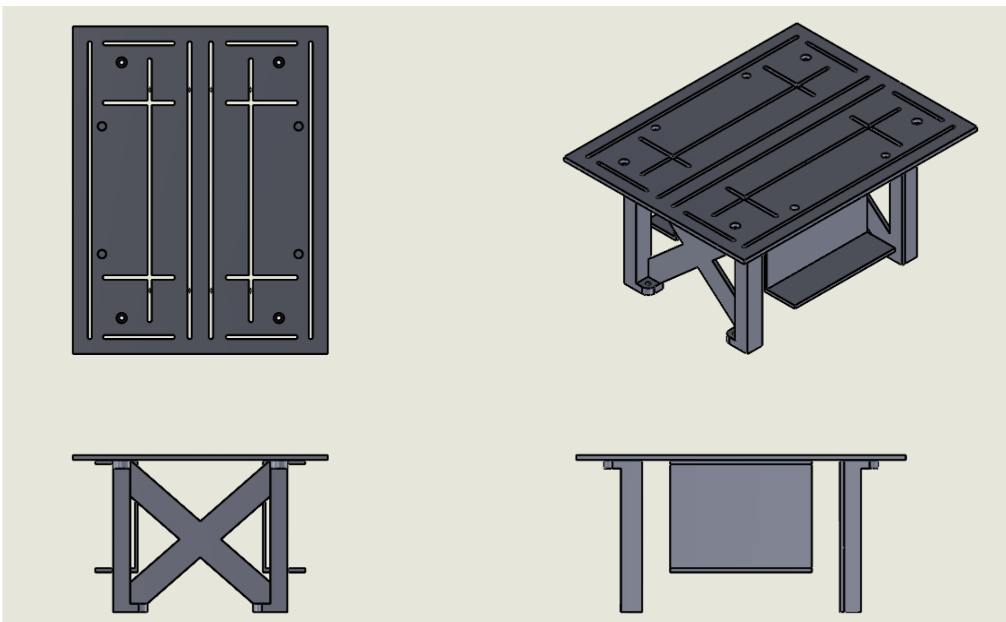

Figure 4. Orthographic and Isometric views of design iteration 2 with controller holders hanging from each side.

- **Design 3**

Our third design proposal features an attachable platform that has holes on the system. These holes are included in the design so that the user can have different configurations when attaching external devices such as a GPU and cameras. The design also features a designated landing zone for the drone as seen in the image below. The landing zone for the drone is extended from the top surface of the system to allow adequate space for the drone to stay on the platform. This landing zone is only extended partially to keep the center of gravity near the center of the robot so that the robot can still perform its full range of motions. Design three also includes a section of the platform that allows the robotic arm to pass through. This would allow the robotic arm to perform all of its functions. As seen in the image above, the design will also include 2 handles for ease of transporting the entire robot. The handles are located near the center of the design to also help keep the center of gravity near the center. While this design should be relatively lightweight due to its simplicity, there is a drawback in that it is one whole part. If a part of the design gets broken, the whole platform would have to be remade.

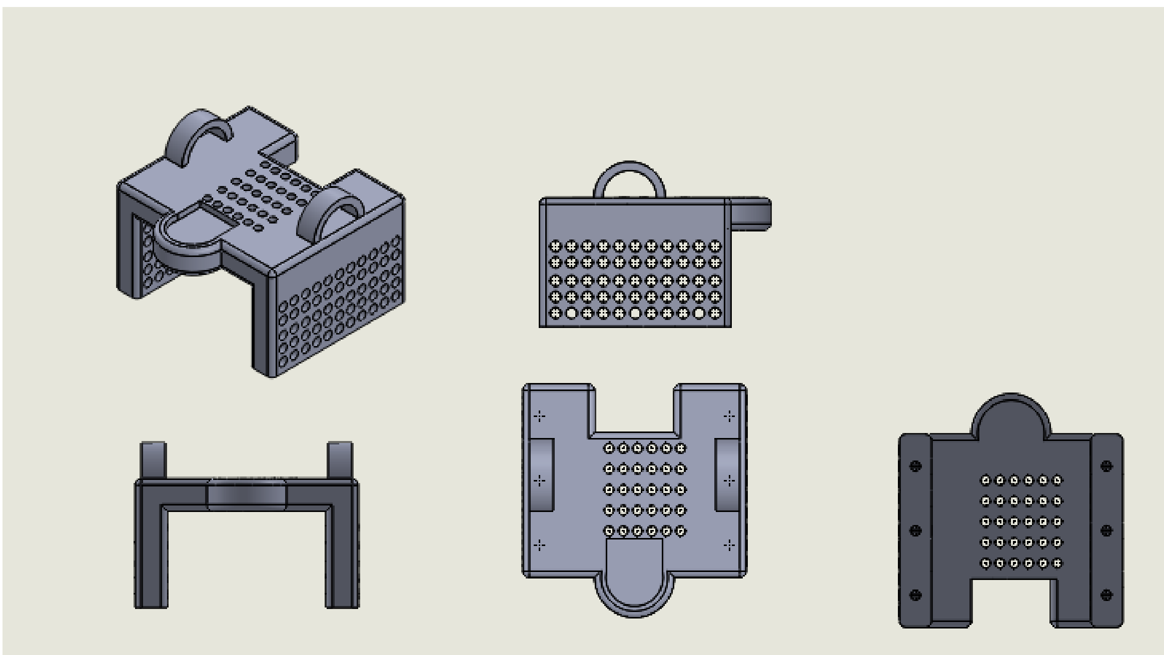

Figure 5. Orthographic and Isometric views of initial design 3 showcasing its modularity and built in handles

Decision Matrix

Table 1. Decision matrix used in determining which of the three initial prototypes to continue with development

	Cost	Durability	Ease of Manufacture	Versatility	Lightweight	Detachability	
Weight Factor	4	2	4	2	5	3	Total
Design 1	3	4	2	5	3	4	**65**
Design 2	5	2	4	3	5	5	**86**
Design 3	3	3	3	4	4	4	**70**

The above decision matrix compares our three design proposals with the following criteria: cost, durability, ease of manufacture, versatility, lightweight, and detachability. The criteria were scored on a scale of 1-5, where 1 is less favorable and 5 is most favorable. In these cases, cost is scored high to low, durability is scored weak to strong, ease of manufacture is scored difficult to easy, versatility is scored less versatile to more versatile, lightweight is scored from heavy to light, and detachability is scored from difficult to detach to easy to detach. The criteria were also given different weighting factors that affected the total score. Each criteria was weighted 1-5, with 1 being less imported and 5 being most important. The designs' scores for each criteria is then multiplied by the weight factor to obtain the total score. The highest possible total score is 100, which would mean perfect scores for each criteria.

Selected Design

With the three design proposals input into the decision matrix, we can directly compare them on the merits based on the different criteria examined. As can be seen by looking at the totals, design 2 had the highest total score among the three options, and thus is the design we will select going forward among these three. Looking closer at each of the criteria, we can examine the differences between the three proposals on each. Lightweight, cost, and ease of manufacture were the three most heavily weighted of the criteria, with each having a weight factor of 4-5. On these points, design 2 was the clear winner due to its relatively slim and easy to produce geometry. For this same reason it also scored highly for detachability, because it would be very easy to attach and remove from the quadruped robot, needing only 4 screws in its current design. Of the remaining criteria, design 2 did score low in durability compared to designs 1 and 3, due to the aforementioned slim design, although this criteria is weighted lower because the sponsor expects the robot to fall and break the mounting system eventually and thus replaceability is more important to the design. For the last criteria, versatility, which refers to the capability of the design to allow for extra utility through the use of additional mounting holes and interfaces, design 2 only scored a 3/5 due to its comparative lack of holes compared to the pegboard designs used in the designs 1 and 3. However, this criteria represents an auxiliary desire of the sponsor, and thus is weighted lower as a result. With all the criteria scored and added, design 2 clearly comes out on top due to its addressing of the highest weighted criteria for a successful design and will thus be our chosen design going forward. In the process of refining our design, however, designs 1 and 3 may be useful for adapting certain ideas and designs to improve our prototype.

Preliminary Results

The house of quality (seen in the table below) evaluates several features and metrics against each other as a score of importance. The two functions/scenarios that the product is evaluated for are the drone platform and arm attached. Each feature for each function is evaluated with a "L" for low (L=1), "M" for middle (M=2), and "H" for high (H=3). Then each feature is evaluated against each metric so that strongly relations between the two are indicated by a black dot (equal to 5), moderate relations are indicated by a circle (equal to 3), a weak relation is indicated by a rectangle (equal to 1), and no relations are indicated by a empty box (equal to 0). The final step is to make a mathematical analysis in which the functions on the same row are added together and then multiplied by the rating of each metric on the same row. The last step was to then add all of the rows that shared the same column together to receive a target score. And one can see in the results below that the cost of materials among the metrics is the most important.

Table 2. House of Quality showcasing the key important metrics that are taken in consideration for the design of the mounting system.

	Drone Platform	Arm Attached	Weight (kg)	Cost of Materials ($)	Yield Strength	Number of Parts	Size
Lightweight	M	H	●	●	○	□	○
Replaceable	H	H		●	□	○	○
Fixable	M	M		●	□	○	○
Durable	M	M	○	●	●	□	
Portable	L	L	□	○	●		●
Detachable	M	M				●	
Modular	M	M		○	●	○	
Versatility	L	L	●	□	●	●	
		Target:	49	115	85	81	55

The table below outlines the failure mode effects analysis for the whole system of the quadruped robot and its various attachments and use-cases with regards to the support system being designed. The FMEA table outlines potential modes of failure, their causes and effects, any current modes of controlling those failures, and potential additional modes of control in each case.

Table 3. Failure mode effect analysis used for designing around potential failures in the mounting system

System	Function	Potential Failure Mode	Potential Effect(s) of Failure	Potential Cause of Failure	Current Mode of Control	Risk Assessment				Additional Mode of Control	Revised Risk Assessment			
						S	P	D	RPN		S	P	D	RPN
Quadruped Robot	A device that can perform actions such that of an actual robot, other than jumping	Failure of Balancing Algorithms	The robot loses its balance and falls over, with the resulting impact potentially damaging other components	User error, unforeseen environmental obstacles	User input, conscientious environment selection	5	10	4	200	Design mounting system to be easily replaceable	3	10	4	120
Drone Landing Pad	A platform to enable drone(s) to land on and take off from the robot safely without causing any damage	Drone fails to achieve take off	Drone cannot fly from positioned on top of the robot	Insufficient landing pad surface area	Design geometry for landing pad	2	3	2	12	Re-design the size of the platform to sufficient size	2	1	1	2
		Drone does not remain stationary while landed	Drone slides off of landing pad	Poor coefficient of friction of landing pad	Material selection	3	7	2	42	Change material type of the surface of landing pad	3	2	1	6
Robotic Manipulator Arm	A device placed on the robot in order to expand its functionality to manipulate its direct environment	Physical impact with environmenta l obstruction	Mechanical and/or electrical failure of the arm Potential mechanical failure of mounting system	High-power impact with fixed obstruction due to user error	User input, conscientious environment interaction	4	3	2	24	None	4	3	2	24
		Arm attempts to lift a weight outside its safe range	Mechanical failure of motors in the arm	Unstable weight distribution	User input, conscientious environment interaction	5	3	2	30	None	5	3	2	30
Handle	A way to let the user carry the robot without causing it harm	Improper material used	Mechanical failure resulting in potential damage of other components	Poor choice in material	Material Selection Design Positioning	6	2	3	36	Choosing better material make-up to withstand load	6	1	3	18
Mounting System	A sizable part to be placed on the robot to lock the robotic arm and landing platform in place	Robot tipping over or moving in a potentially harmful manner	Mechanical failure resulting in potential damage of other components	Poor design results in failure	Design Positioning	3	8	3	72	Stronger design to withstand conditions	3	5	2	30
				Poor material choice	Material Selection	3	8	3	72	Choosing stronger material to withstand conditions	3	5	2	30

Validation/Verification

To verify and further validate the design prototype to ensure it meets the requirements laid out by the sponsor, several tests are to be conducted with the final design of our mounting system. The tests are specified in the failure mode effect analysis table and can be tested both in ANSYS simulations as well as in the lab. The tests can be seen in the table below.

Validation	Verification
Landing Pad	Test the landing pad by landing the drone and verify that the drone has sufficient room for landing and takeoff on the landing pad. Additionally, the drone should not slip off the landing pad. Tests will involve drone landing on the landing pad being subject to multiple stops and starts of the quadruped in multiple directions to validate.
Support System Modularity	Test the mounting system’s modularity by attaching various attachments to the mount such as camera GPU, robotic arm manipulators, and other various tools/gadgets. Test is pass/fail depending on if everything fits.
Support System Integrity	Test the support system’s structural integrity by attaching the robotic arm to the platform while extended laterally with a full payload to observe any deformation or structural failure of the system. Tests are considered passed if the support system holds together while the arm is in use, fail if otherwise.
Carry Handle	Test the improved carry handles by affixing it to the quadruped while the support system is engaged, and then lift the entire quadruped and support system by the handle(s). Test is passed if no structural failure occurs.
Support System Stress Test	Test the support system’s attachment strength to the quadruped robot by having the robot engage in its “beg”, “strut”, and “jump” routines, subjecting the system to a variety of force vectors. Test is passed if no structural failure occurs.

Table 4. Validation/Verification table to ensure sponsor needs are met

Design Iterations

Prototype 1

➢ **Method**

The prototype was designed with laser cutting and 3D printing as a means of fabrication in mind. Several tracks were incorporated into the platform so that the positioning of the robotic arm base can be specific to the sponsors needs. Furthermore, the platform was made to fit snugly within the boundaries of the A1 quadreped’s main body. This is so that the limbs of the quadruped can move freely about the outside of the main body without receiving any interference from the platform. Additionally, the platform can act as a natural landing pad for the drones with its spacious design. Furthermore, there were four holes in the right and left sides of the platform in which the two controllers could be affixed with screws. There were four more holes placed on either end of the platform in which the two support trusses could be attached via two pairs of screws and nuts. These support trusses are two 3D-printed pillars with a X-shaped cross section connection. This overall design (in reference to the cross section and the significant space between the two supports), is so that the sponsor and his student workers would be able to manipulate any analogs, ports, switches, or controllers that they stated that they would want to be able to easily manipulate and otherwise interact with.

The platform was created with a clear, 0.2 inch thick acrylic plastic plate. This material was chosen because it would be able to be shaped easily using a laser cutter and the transparency function provided by the material would allow the sponsor and his workers to easily see all aspects pertaining to the controllers and screws that would be used in mounting. This feature is useful because this allows the sponsor to more easily identify any issues that could be seen with their experimental set-up. Furthermore, the supports were created using 3D printed PLA plastic due to its rigid nature and its low chances of deformation from FDM printing. It should be noted that the reason why these means of fabrication were chosen is because the problem definition stated that the parts would need to be easily replaceable (low cost, quick fabrication, accessible means of reproduction, etc.). With this and the availability of the Makerspace and its project submission/completion process, it was decided that the team and the sponsor would use the Makerspace to fabricate the prototype and final product's replacement parts.

The selection of screws was initially picked based on the mounting points of the A1 quadruped, controllers, and robotic arm. The controllers and A1 quadruped use M3 socket-head screws of varying lengths, these screws are long enough to securely fit within the mounting points of the controllers and affix the design supports to the platform and the top of the A1 main body. We intend to use M2.5 socket-head screws to attach the robotic arm base to the top of the platform due to the screw hole constraints in the robot arm base.

The sponsor requested that the team come up with a solution to the old handle that is currently installed onto the quadruped robot. The current handle was a single nylon strap that was worn out from frequent use for lifting and carrying the robot. The strap was screwed onto the quadruped with washers and two hex screws. The team thought it was best rather than designing and fabricating a new handle for the quadruped to look into existing alternatives that are available for purchasing. After measuring the existing handle it was found that the length of the handle was about 7 inches and then research was conducted to find alternatives with that length in mind. Additionally, another idea that was had while exploring new handles was to avoid rigid and firm handles that cannot bend and twist while carrying the quadruped. This was in mind so that the user carrying the quadruped can have that same ease of use and retain the ergonomics of holding the quadruped. Finally after researching numerous handles the final selected handle was that of a kayak handle. It held the same length and material as the original but was further reinforced with rubber grips on the handle for greater stability while carrying the robot. The kayak handle was also rated for carrying weights of up to 60 pounds which is more than sufficient for carrying the quadruped. Finally the kayak handles are mounted in the same manner with screws and washers and is a very cheap replacement to the original costing less than $10.

➢ **Results**

Once the initial prototype had been assembled, the prototype was tested at the UIC Robotics Lab for basic functionalities. The prototype was firmly affixed to the robot with the manipulator arm safely attached to the prototype. The prototype was attached on the top of the robot and was able to rotate at a 90° angle. When the basic locomotion of the robot was tested with the prototype attached, the support system stayed firmly attached without any failure. The robot was able to walk within a straight pathway at an average speed and when the pace quickened, it was still able to function. The robot was able to initiate its "beg" maneuver in which it leans back on its hind legs a full 90°, and the prototype with manipulator arm equipped stayed attached successfully. Lastly, lifting the robot from the support system itself was successful; there was no failure or damage done to the system.

Following the success of the in-lab testing of the first prototype, the team set up a series of structural analysis simulations using ANSYS to test our design under various circumstances. There were 5 simulations set up to test the support system: two testing the manipulator arm, two testing high-speed impact, and one testing the response to lifting the entire quadruped by the support system. For the two simulations testing the manipulator arm setup, we examined the scenario where the arm is outstretched and lifting its full payload - one where the arm is parallel to the quadrupeds centerline, and one where the arm is perpendicular. The results of these simulations can be seen below, with the prototype successfully maintaining structural stability.

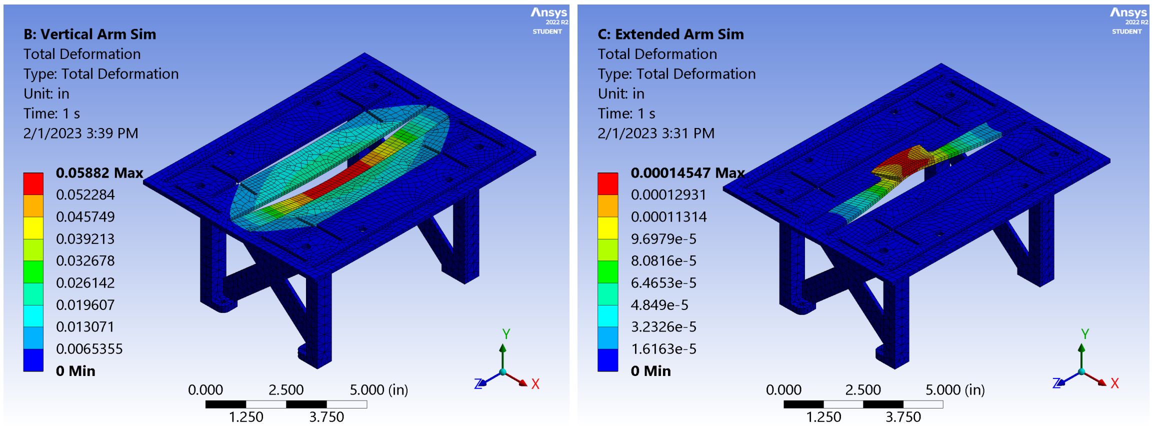

Figure 5. ANSYS Simulations for total deformation on platform for lifting objects while the robotic manipulator arm is extended fully horizontally and vertically while carrying its max payload. Units are in inches.

For the two simulations testing high-speed impact, the maximum ground speed of the quadruped was taken into account to test the scenario where the robot might crash into an obstacle with the prototype taking the full impact. This was tested with both a head-on collision as well as a sideways one from the quadruped strafing into an obstacle instead. This scenario is one where the support system is expected to fail, as it is not designed to withstand an impact as such, but rather be easy to replace in such an event. As expected, the design failed catastrophically in this simulation, buckling and likely snapping the plastic in multiple locations.

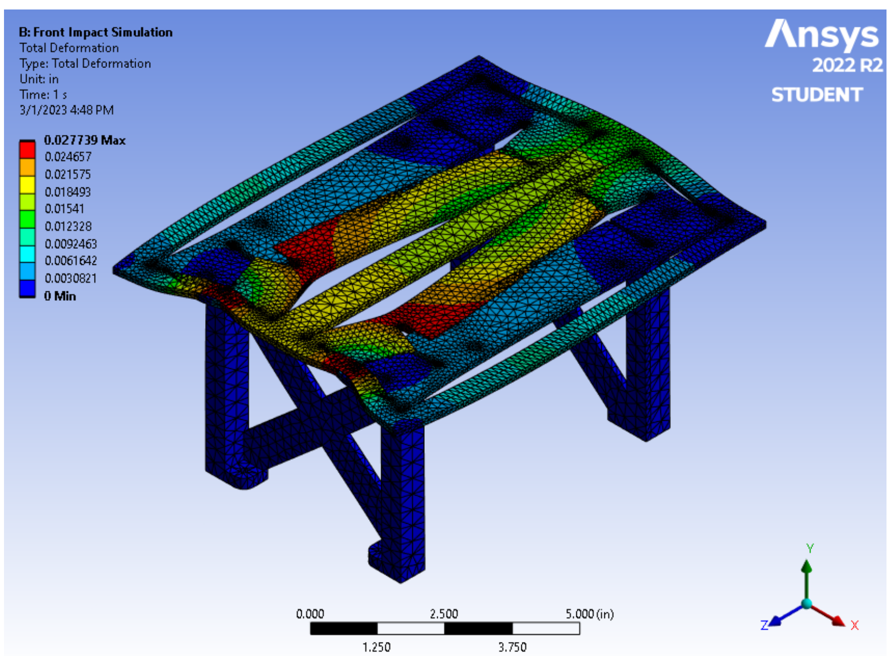

Figure 6. ANSYS Simulations for total deformation on platform and trusses while the quadruped robot experiences a worst case scenario crash whilst at top speed with the impact on the front of the platform. Units are in inches.

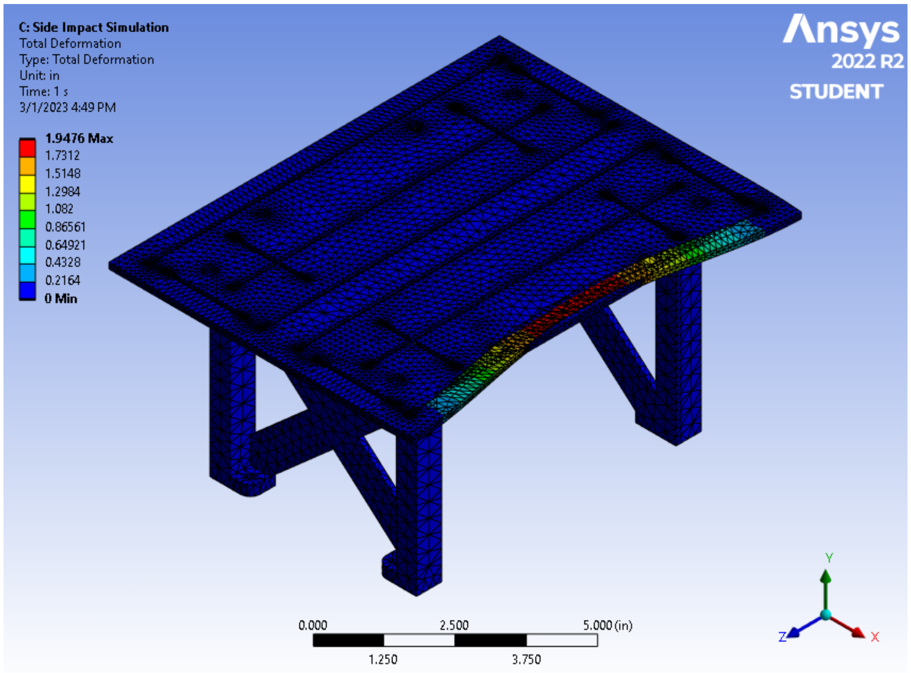

Figure 7. ANSYS Simulations for total deformation on platform and trusses while the quadruped robot experiences an impact on the side of the platform. Units are in inches.

For the last simulation, the prototype was simply simulated lifting the mass of the robot underneath. This test had already been performed in the lab, and the design succeeded in supporting the full weight of the robot without failure. As expected, the design passed the simulated test as well.

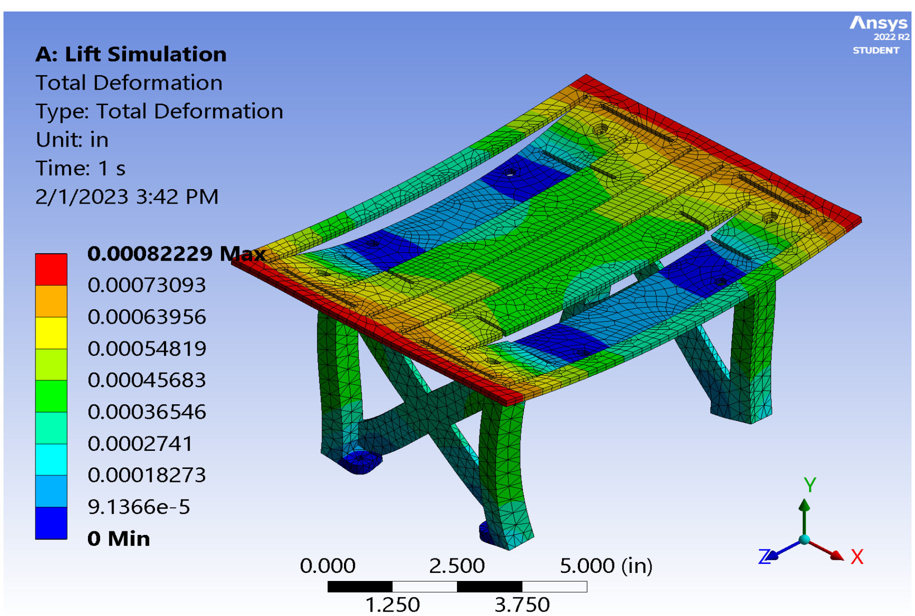

Figure 8. ANSYS Simulations for total deformation on platform and trusses while the platform is manually lifted by the top from its sides as a sort of last resort handle. Units are in inches.

➢ **Proposed Changes**

After the sponsor saw the initial prototype, a few modifications were suggested for the final design. The first of which was the extension of the platform. The sponsor wanted the platform extension to allow more space to include additional attachments. The second suggestion was including additional holes to allow different mounting positions for the external components. Another suggestion was modifying the truss design to allow easier access to the components on the robot's back; raising the trusses was also mentioned in addition to the truss redesign to allow better clearance for external components situated underneath the platform. It should also be noted that the sponsor mentioned the idea of modifying the design to allow it to be stacked upon itself, with multiple platforms in use. The team has taken this suggestion into consideration when developing the second prototype but will need to revisit this idea at a later date.

Prototype 2

➢ **Method**

With the initial prototype support system design completed and tested, the team moved forward with iterating and improving upon the design to better meet the sponsor's desires for the product. The team proceeded by beginning designing alternate variations on the existing models for the platform and the truss supports. Once these design alternatives were finalized, the next step is to test the new design with our previously set up ANSYS simulations to compare its performance to the existing design to determine if the new version is a suitable replacement.

Following the sponsor feedback that the truss supports could be made less obstructive to allow better access to the ports on the robot's back, the team proceeded to produce a number of alternate redesigns. Given the relative simplicity of the truss geometry, this was a rapid process of design iteration that resulted in 5 additional truss variants. Because the initial, X-shaped truss was more than sufficient from a structural stability standpoint, each design variant involved reducing the footprint of the supports for the truss legs, as well as lengthening the legs themselves to allow the platform to sit higher. These new truss design variants are shown below, arranged in order from most- to least-stable.

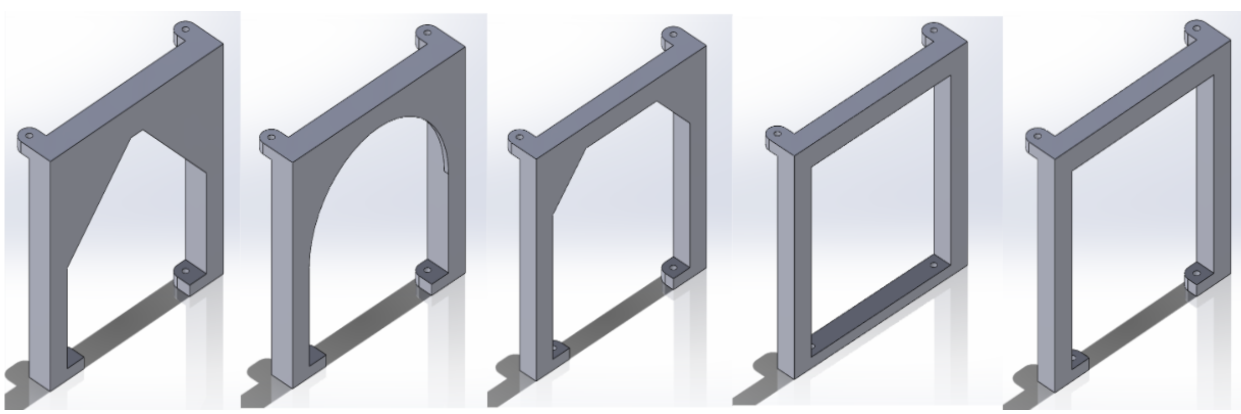

Figure 9. Several redesigned support legs using the recommendations requested by the sponsor.

To determine which of these support legs will be used going forward, several ANSYS simulations were performed with the same configurations as prototype 1 with regards to the lift simulations in particular. The support legs were put under the same testing conditions (lifting with max payload and using the original top) and taking a look at their total deformation the safest support leg was chosen. Two support legs were tested: the roman arch design (Fig 9 support leg 2) and the N-leg design (Fig 9 support leg 5). The support leg featuring the roman arch was ultimately chosen for the final design of prototype 2.

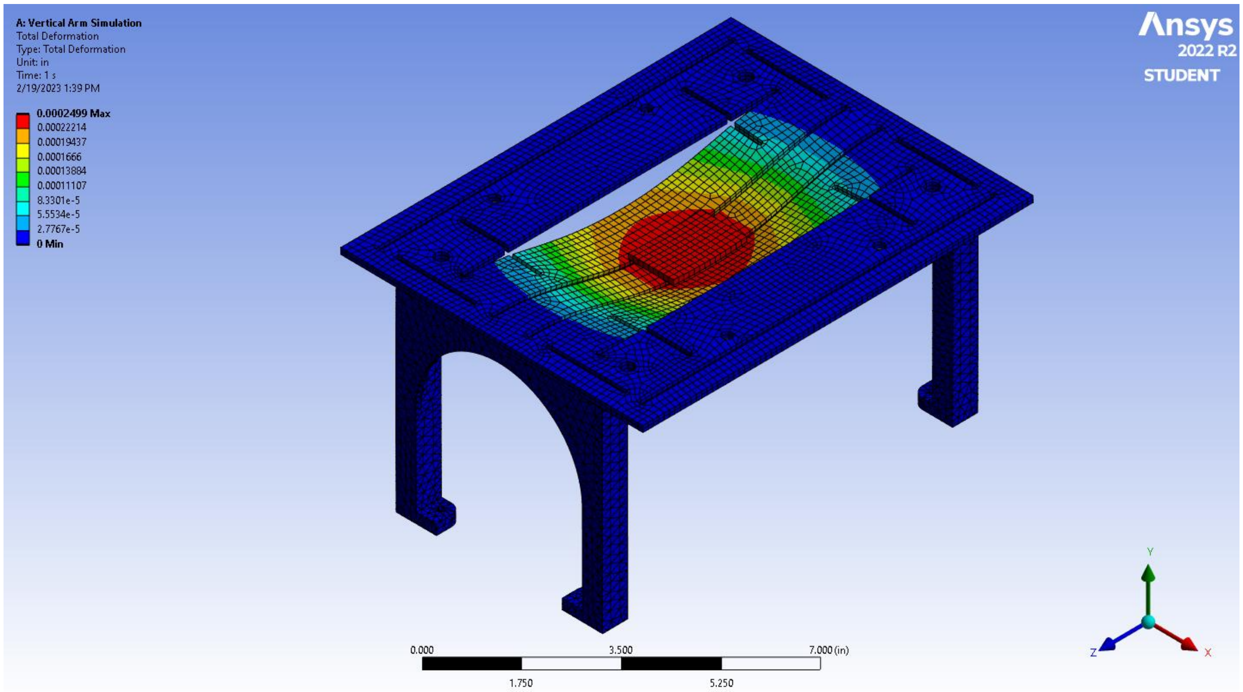

Figure 10. ANSYS simulation for total deformation featuring the roman arch design for the support legs during the vertical arm simulation. Total deformation is slightly better than that of the N support leg and similar results were found in the extended arm simulation. Units are in inches.

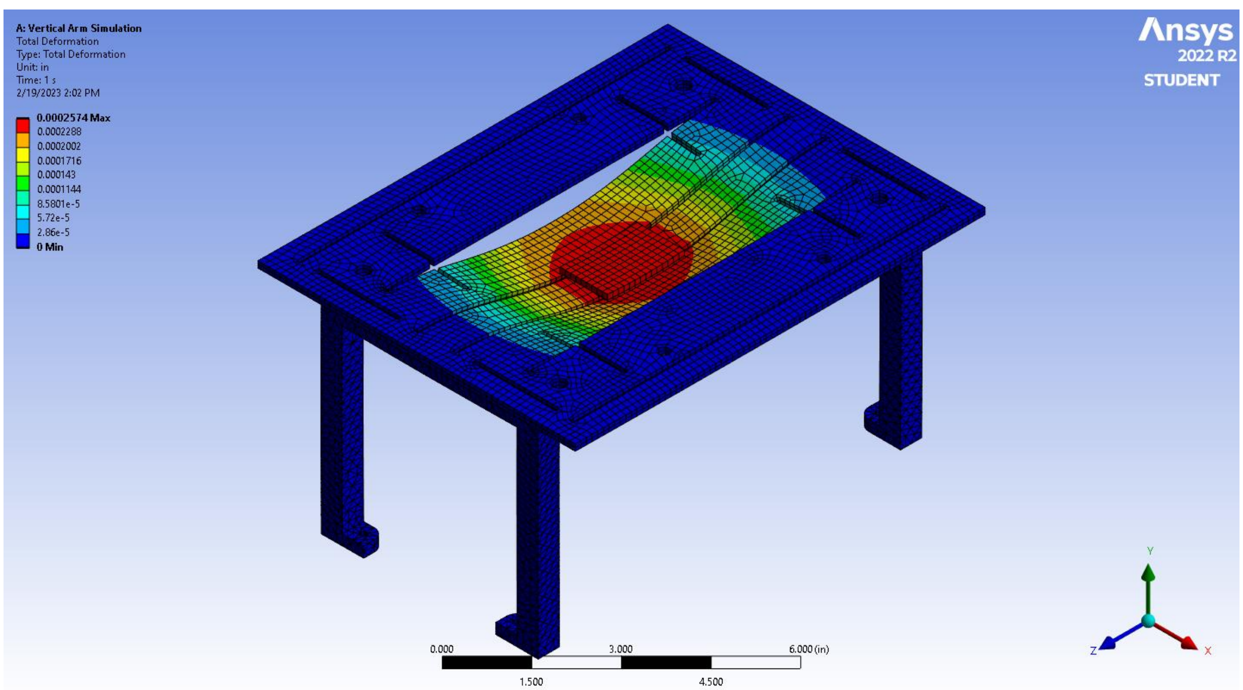

Figure 11. ANSYS simulation for total deformation featuring the N leg design for the support legs during the vertical arm simulation. Units are in inches.

In the second version of the prototype, the team combined ideas from the two different designs of the platform. One of the designs involved additional numerous holes that allowed various configurations for external components such as a camera and controllers. This design also featured a rounded platform extension to store a third controller underneath.

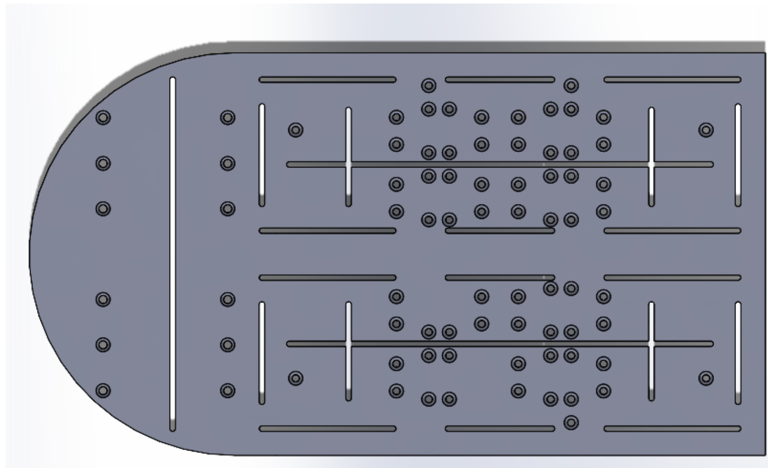

Figure 12. A redesign of the existing top platform using the feedback given by the sponsor.

The second proposed design modification was similar to the first prototype but included more tracks, holes, and an extended rectangular portion to store the controller underneath.

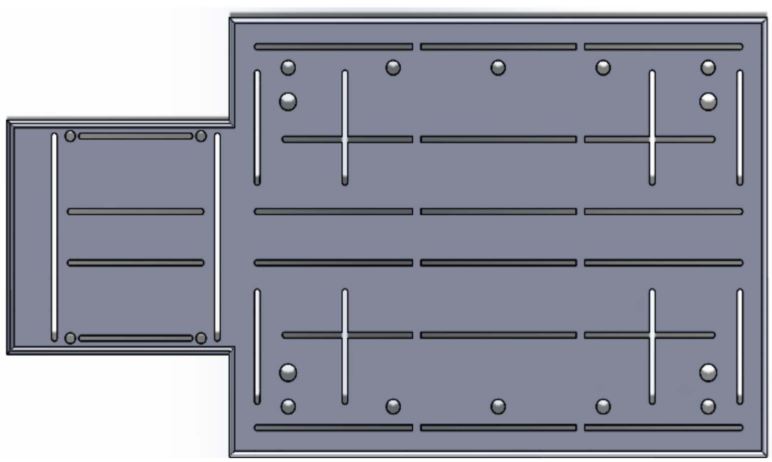

Figure 13. An alternative redesign of the existing top platform using the feedback given by the sponsor.

The group decided that the platform with numerous holes would be kept since it allowed the sponsor to configure the attachment in any way they pleased. However, some modifications were made to this design. The long horizontal track along the extended platform in the second proposed design proved to be unstable as it would be prone to breaking if a strong enough force was applied. The first modification that was made was modifying the long center track. The new design features two smaller horizontal and vertical tracks that will still offer the sponsor configurability with the attachments while having more support. The amount of holes on the extended platform was also revised by only offering 6 holes instead of the original 8 on one of the proposed designs. The second modification that was made was the rearrangement of the holes. Some of the holes in the design proposal were not placed efficiently and would have caused the platform to be unstable.

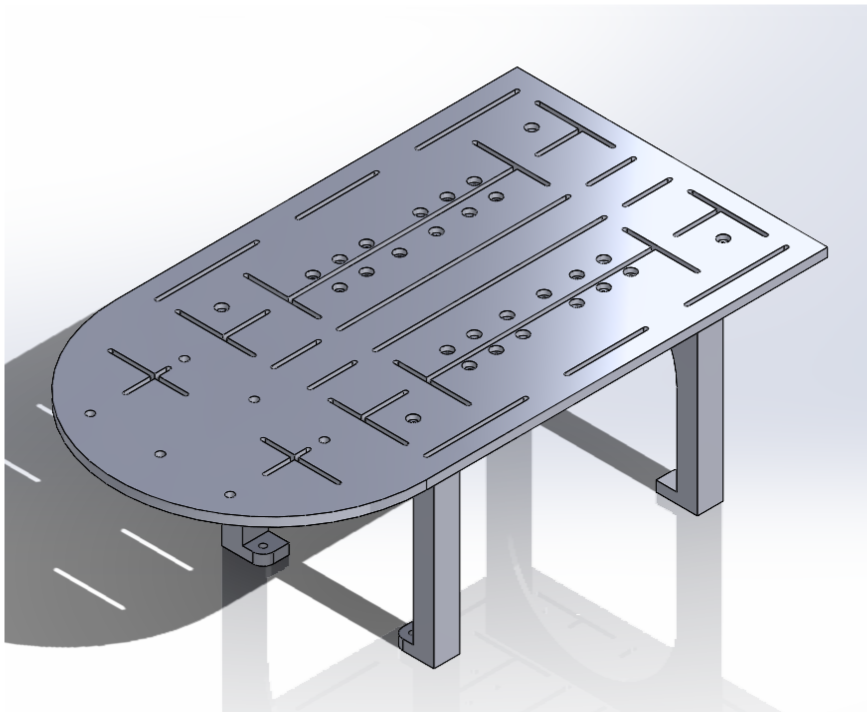

Figure 14. Using all the recommendations from the sponsor this was the team's assembled design for the second prototype for the mounting system, the quadruped robot.

- **Results**

Following the successful redesign and CAD assembly of the support system, structural analysis of the new prototype was conducted under the same parameters as the original prototype. In the first two structural analysis simulations, the prototype was subjected to testing when the robotic arm was in both its vertical and extended positions.

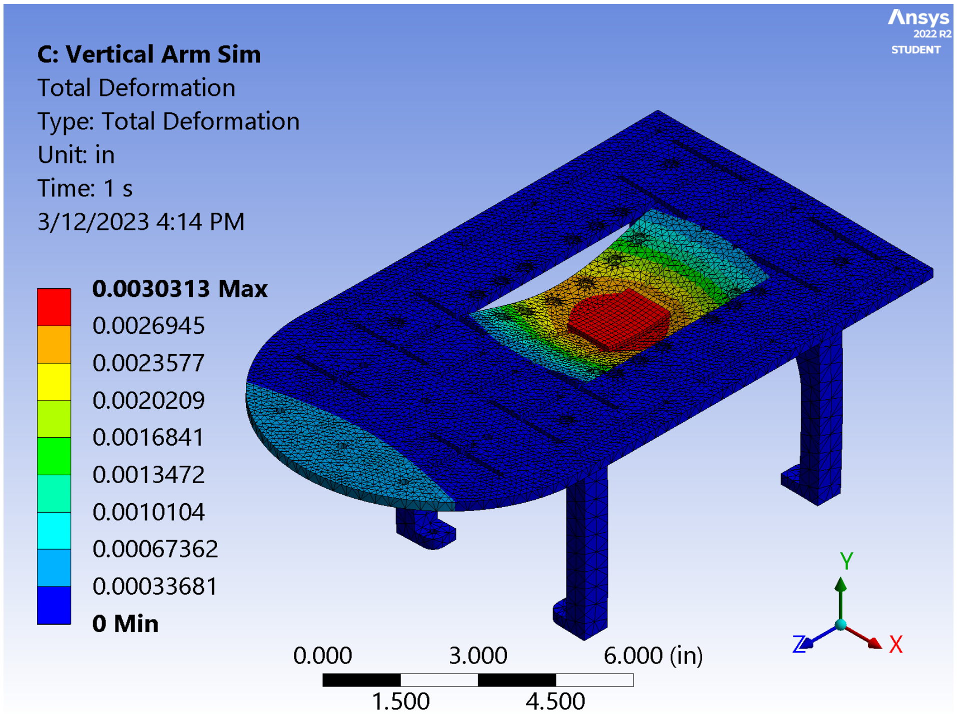

Figure 15. ANSYS simulation for total deformation during the vertical arm simulation featuring the robotic manipulator in the center of the platform. Units are in inches.

It can be seen that in both arm simulations, the redesigned support system showed reduced maximum deformation. The deformation in the new prototype for the vertical arm sim has a max deflection value of 0.003 inches which is 5% of the deformation that was found in the old prototype.

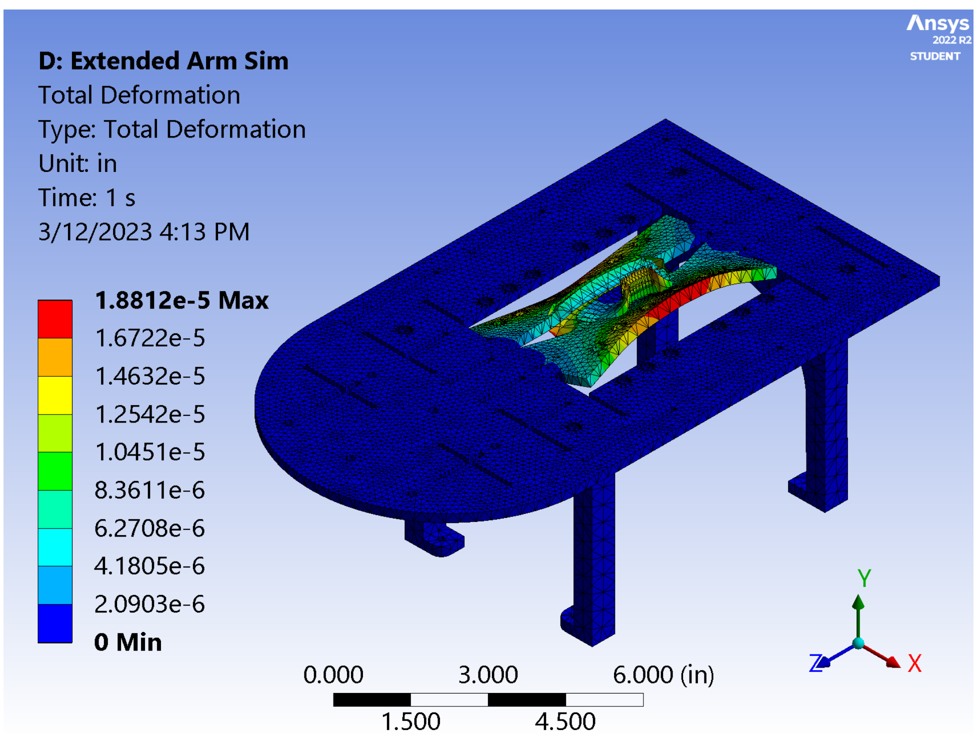

Figure 16. ANSYS simulation for total deformation during the extended arm simulation. Units are in inches.

The extended arm simulation also showed a reduced degree of deformation, with the original design showing a maximum deformation of 0.00015 inches and the new design having a maximum deformation of 0.00002 inches, another near 10x improvement.

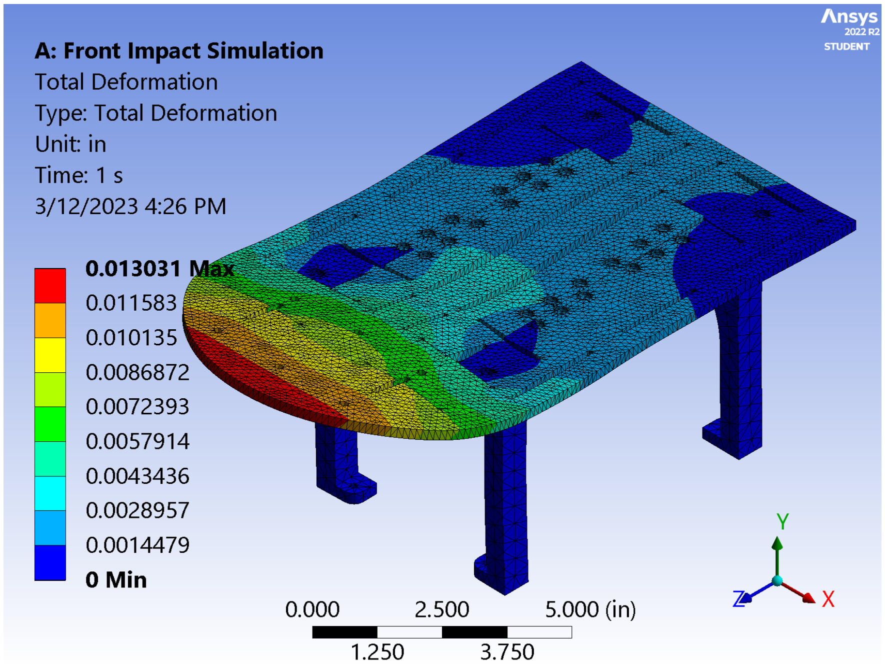

Figure 17. Further ANSYS simulation for total deformation during frontal impact test. This test is for a worst case scenario where the quadruped runs at top speed and crashes into an object. Units are in inches.

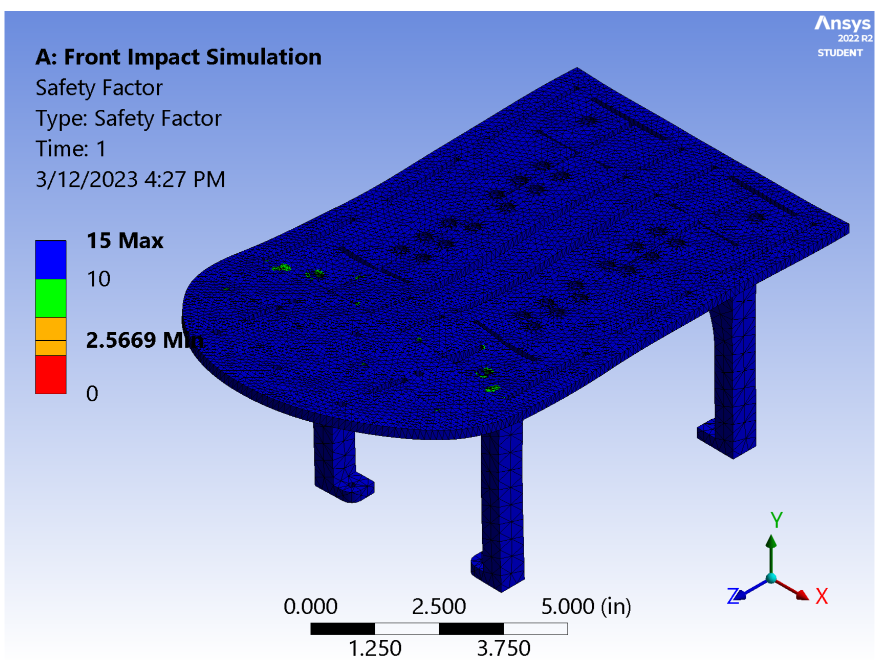

Figure 18. The subsequent ANSYS simulation for safety factor during frontal impact test. The prototype is expected to survive this impact with a safety factor larger than one being 2.56.

The front impact simulation was also assessed for this new prototype. The max deformation has a value of 0.013 which is half the max deformation of the front impact of the previous simulation of 0.0277 inches. More significant however is that the safety factor for this simulation is now above 1, compared to the initial prototype which failed.

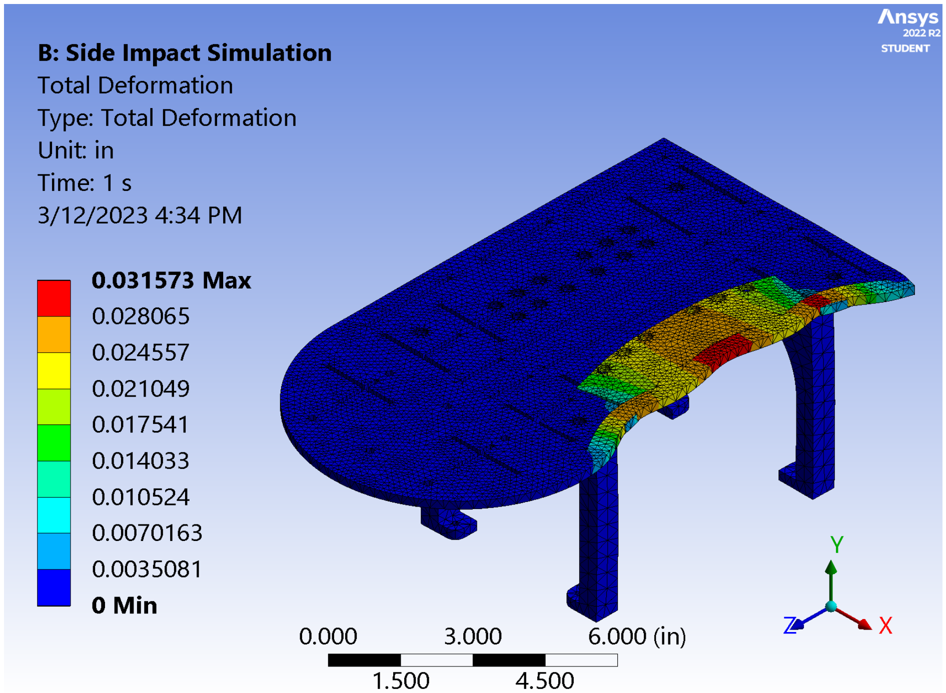

Figure 19. ANSYS simulation for total deformation for the test of an impact on the side of the mounting system. Units are in inches.

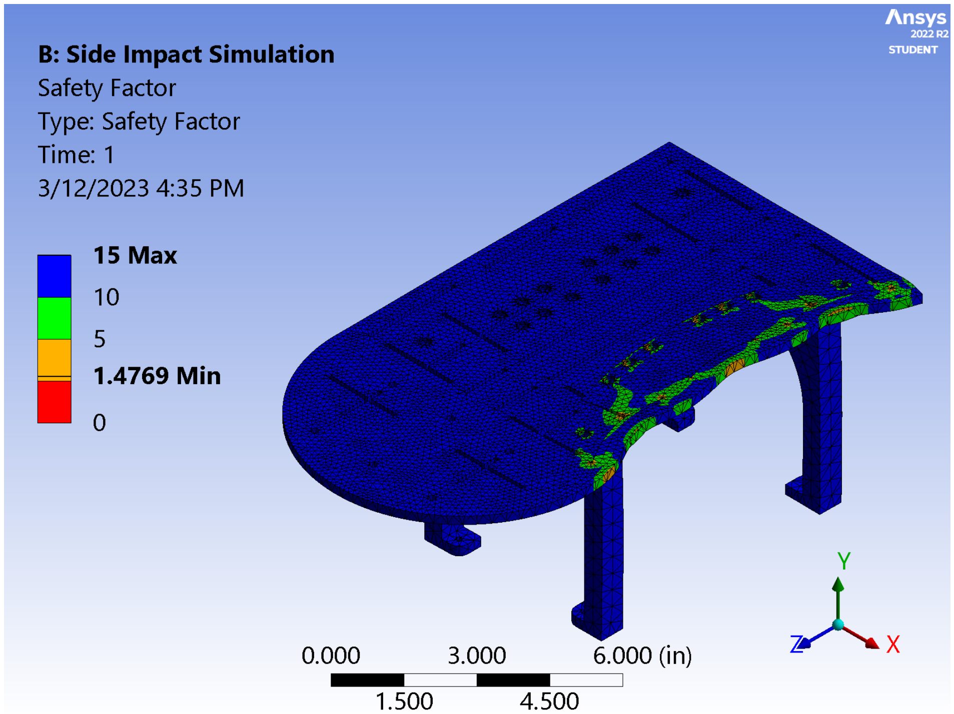

Figure 20. Subsequent ANSYS simulation for safety factor for the test of an impact on the side of the mounting system. The mounting system is expected to survive the impact but it is best to avoid this impact due to the safety factor being close to failure being just over 1.

The side impact was simulated in similar matters. The deformation was located on one side of the platform and has a maximum deformation of 0.0315, down from 0.076 from the initial prototype. Once again, a decent improvement.

Overall, the redesigned support system shows marked improvement in all four scenarios that it was tested for in ANSYS. This is encouraging as we move to the next step of manufacturing the second prototype and performing real world design validation.

The validation testing for the second prototype was mostly a success. The support system was able to withstand the weight of the manipulator arm and drone, and held up well during normal locomotion of the quadruped. Additionally, the rubber trim edge guard was successful in preventing the quadcopter drone from sliding off the platform while the quadruped was in motion. However, when performing a stress test in which the quadruped shook violently and jumped up and down repeatedly the rear support truss experienced structural failure, snapping off at the location of the screw.

The proposed changes revolved around the truss of the support system. The truss snapped where the bolts were screwed in to hold the platform. In order to compensate for the failure, filets were made at those positions to reduce the stress applied when the quadruped is in motion. Additionally, it was noted during assembly and testing that the trusses overlapped with some of the holes and tracks in the platform when attached, so the next iteration will redesign the hole placement to account for this.

Prototype 3

➢ **Method**

After the initial testing of prototype 2, the team decided that there needed to be minor revisions to improve the current design. The first revision to be made was to shift the holes on the extended portion of the platform to allow more clearance when the controller is mounted. The holes were approximately shifted by a quarter inch. These holes were also slightly modified to create a tighter fit for the screws by using the hole wizard tool on SolidWorks. The next change was to modify the tracks on the current prototype. When assembling prototype 2, the team noticed that some of the track placements overlapped with the truss. To rectify this, the team shortened areas of the track that interfered with the truss. An additional "H" slot was also added to the extended portion of the platform to allow more configurability. The team also modified the current roman arch truss legs to help improve the structural stability of the design. One of the problems the team faced was with the limitations of 3D printing. Since the legs of the truss are 3D printed, they are more susceptible to breaking when compared to using a solid material. The new truss is thicker in areas in which the truss would be in contact with the platform. This includes the upper horizontal portion of the truss and the extended heads where the screws would be located. Increasing the thickness in these areas help overcome the limitations of 3D printing. Filets were also applied to areas around the extended heads to help the structural stability.

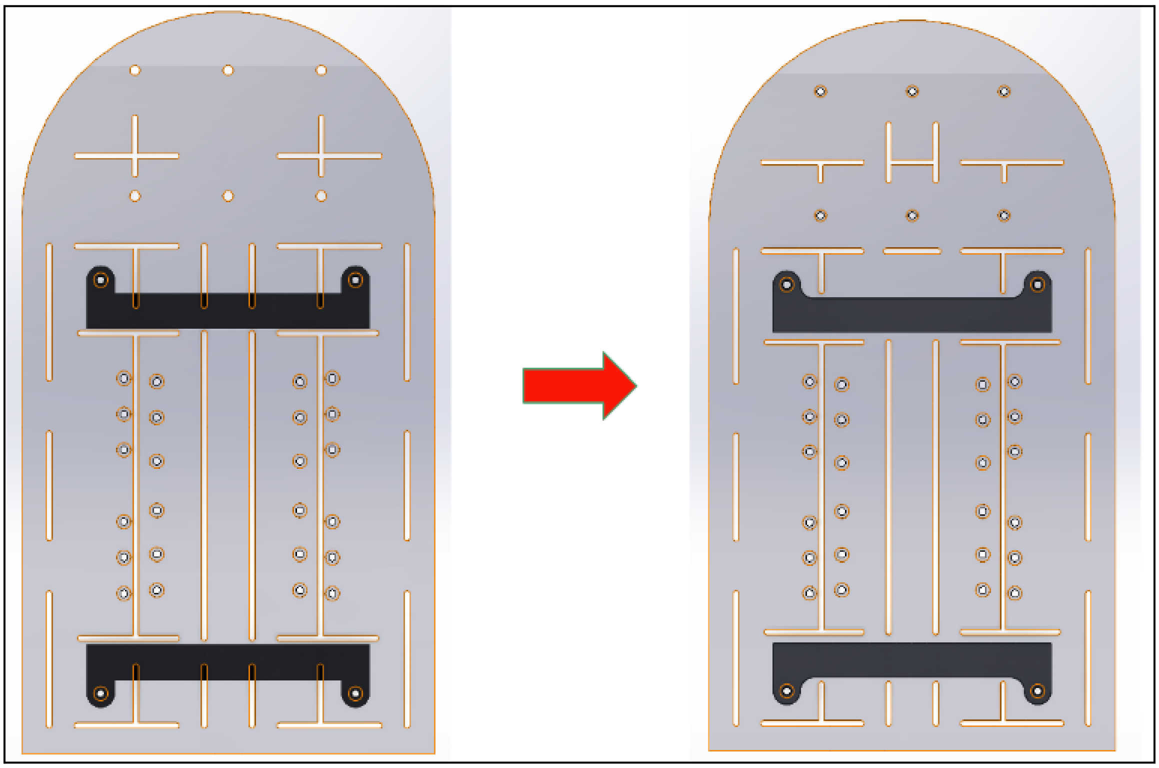

Figure 21. Visual depicting the updated platform highlighting the updated track and hole placements for the third prototype.

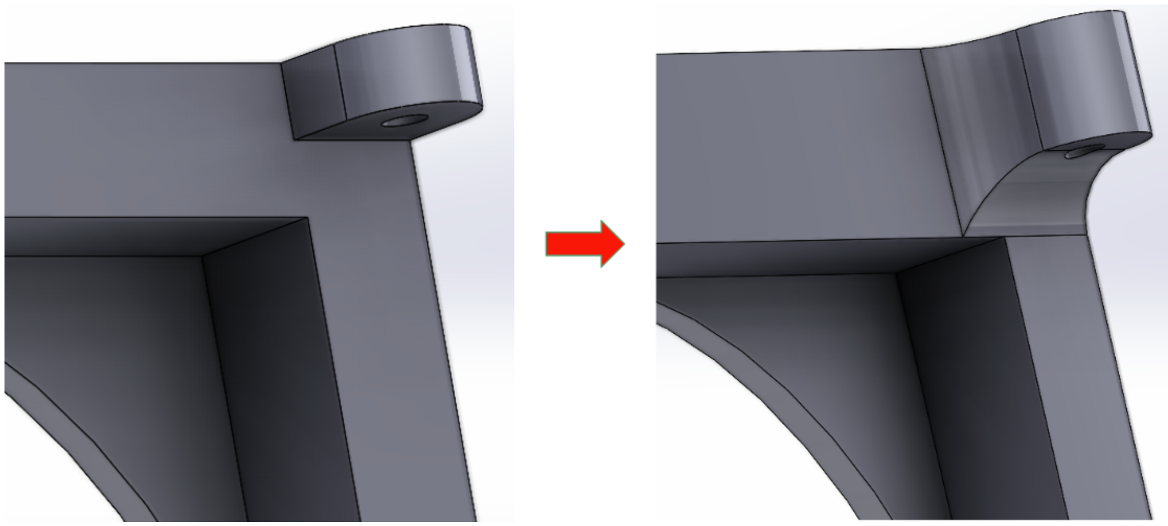

Figure 22. Visual depicting the updated truss showcasing the reinforcement where the original truss snapped.

- **Results**

Much like the previous version of the support legs, the updated truss was still able to support the manipulator arm, drone landing, and controller attachments. It was able to withstand the stress factor of the quadruped system under basic commands, but as the team expects the truss to fail under the quadrupeds more advanced movements the team did not perform the stress test as there was not enough time to print another set of legs in case of failure with the engineering EXPO around the corner. The redesigned platform also performed as expected since there was no extreme redesign done to it. The deformation and structural integrity of the platform were minor and reflected the ANSYS tests done in prior iterations of the prototype.

Device Specifications

Specification	**Value**
Platform Width (in)	7.5
Platform Length (in)	13.44
Platform Thickness (in)	0.2
Truss Height (in)	5.0
Truss Width (in)	5.13
Truss Thickness (in)	0.63
Platform Material	Acrylic
Truss Material	PLA
Rubber Trim (McMaster Item No.)	8507K44
Screws (Arm/Controller)	M2.5
Screws (Truss)	M3
Platform Cost	$8.40
Truss Cost	$3.35
Rubber Trim Cost	$17.50 / 10 ft

Conclusions/Future Work

When the support platform was tested in the lab, there were no failures seen at hand. Although the first prototype was successful, after consulting with our sponsor there were minor adjustments and redesigns done to further improve upon it. The redesign process involved two main steps, producing design alterations for both the support trusses and the platform, which resulted in a better realized version of the sponsor's desired product. Designs were initially created in SolidWorks and later verified with ANSYS to reduce the time and resources of manufacturing multiple prototypes. After verifying, manufacturing, and testing each prototype the group was able to come to the third and final prototype which is able to meet the sponsor's needs. Although the team was able to optimize the modularity of the tracks and holes of the platform, the sponsor still expresses additional ideas that can even further improve the support system. Such ideas that the sponsor would like to explore is the idea of creating a second platform that would allow it to stack on the first platform. Other ways that can further improve on the system is the development of additional platforms for the quadruped in which there can be a platform with no tracks/holes so that the drone can have the maximum clearance needed to land and takeoff. Or yet another platform where the quadruped can take on different controllers and thus different configurations for testing and research.

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