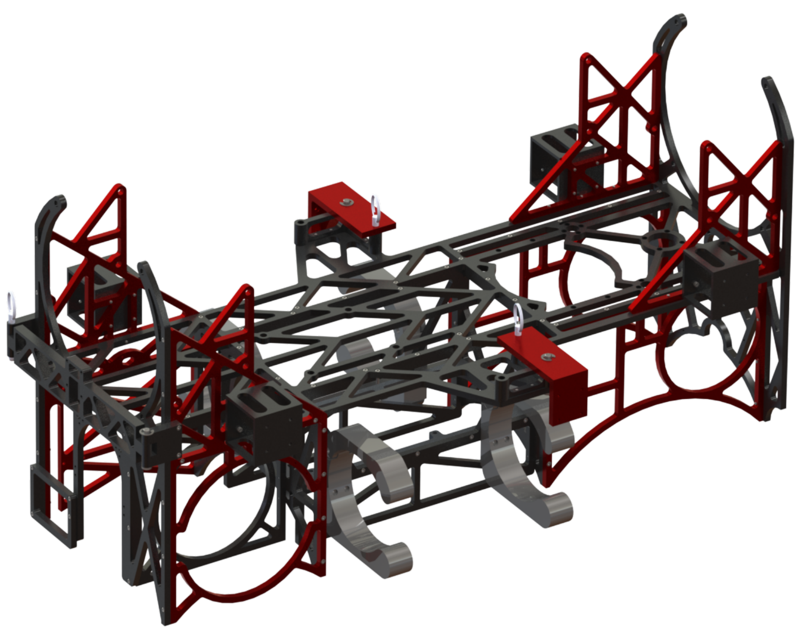
Cornell University Autonomous Underwater Vehicle Team

Spring 2021

Aurora Frame



Technical Report

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Contents

1 Abstract

The frame is the backbone of the autonomous underwater vehicle's (AUV's) structure, securing all enclosures and additional components around the main enclosure, the upper hull pressure vessel (UHPV). The frame is largely responsible for how the submarine interacts with its environment. Component placement and mounting affects buoyancy, the functionality of the enclosures and components, and the protection of these components from damage on the ground or in the water. Beyond constraints and objectives common to all projects on the team, such as manufacturability and sufficient safety factors from typical loading, the frame design considers the specific restrictions and objectives of each enclosure and component. These specific objectives are balanced with the broader objectives of the vehicle, such as reducing pitch and roll, maximizing enclosure accessibility, and organizing enclosures in a spatially efficient manner. The frame design alone dictates vehicle layout.

2 Design Requirements

2.1 Constraints

- Must securely mount all enclosures (Table 1) and additional components (Table 2) according to component restrictions
- Must be manufacturable
- Must not deform from typical loading conditions
- Must be contact surface between the AUV and the ground
- Must protect critical components
- Must fit through standard doorways

2.2 Objectives

- Reduce pitch and roll of AUV through enclosure placement
- Minimize weight and size of frame
- Allow for easy access to components, especially those that are frequently removed
- Dedicated and intentionally-placed space for cable routing, weights, and foam
- Convenient placement of handles

3 Previous Designs

3.1 Argo (2015)

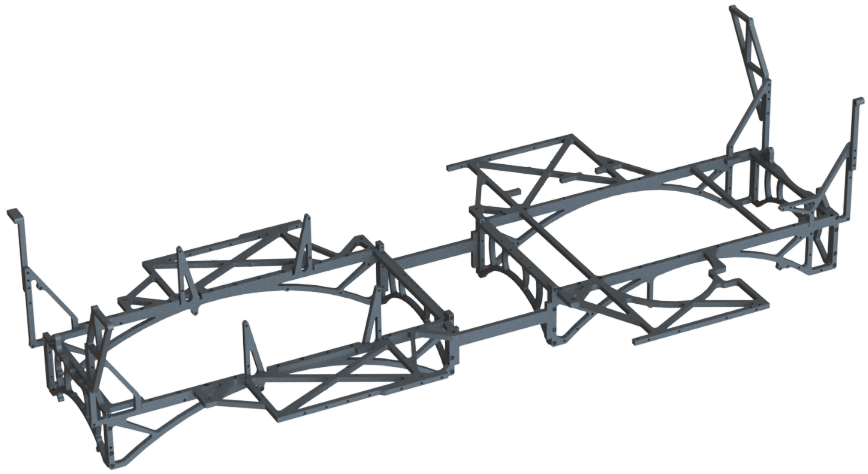


Figure 1: Argo Frame

Argo's frame, though very lightweight and extremely compact, bent excessively in its middle portion, resulting in a corresponding misalignment and unnecessary stress on the vehicles two main hulls, which somehow were still able to seal. The frame deflected around nearly every other enclosure as well - the eight thrusters were all poorly secured and vibrated easily. The largest design oversight was the lack of lifting handles. Several more components were either not designed with a mounting scheme in mind or were changed, which led to some hastily redesigned mounts and a few components being secured by cable ties and hose clamps. CUAUV paid out of pocket for most of these new mounts to be fabricated in the Clark Machine Shop,which contributed to a budget deficit which was then inherited by the 2015-2016 Team. Argo's frame was initially planned to be roughly waterjet cut and then finish CNC milled, however because of time constraints the CNC milling did not occur, leaving a rough surface finish and many misaligned connections, such as those for the hinged sway thrusters.

3.2 Thor (2016)

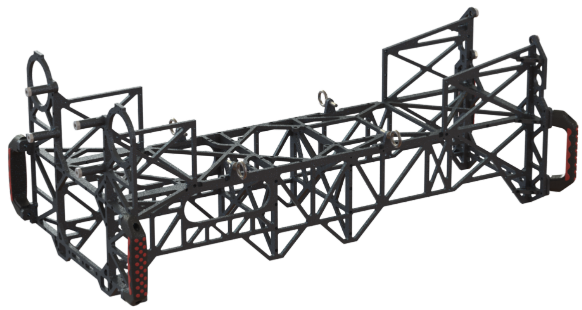


Figure 2: Thor Frame

Thor's frame design aimed to fix the issues that were present in Argo's frame design, principally Argos frames large deformations, long manufacturing time, misalignment, and poor vehicle serviceability. Thor's frame utilizes the spaceframe concept implemented from Killick (2012) onwards. The frame pieces, however, do not use the T-profile found in earlier frames in an effort to decrease manufacturing time by only requiring waterjetted parts and adding holes, since this was an issue last year and it is necessary that the frame be entirely completed in order to assemble the barebones AUV and perform the first in-water testing. This, in addition to increased emphasis on stiffness and vehicle size, came at the price of a heavier vehicle frame.

Thor's frame worked well in that it successfully avoided Argos problems of structural integrity. It was easy to carry though the vertical handles were uncomfortable at times, and most components were easy to mount and unmount, though some enclosures with dual purpose sealing/mounting holes proved problematic. Additionally, the thruster wings allowed the thruster streams to not interfere with each other or SEACON wires. The biggest complaint was that Thor's frame was fairly bulky, but getting the frame waterjetted allowed for ease of manufacturing.

3.3 Artemis (2017)

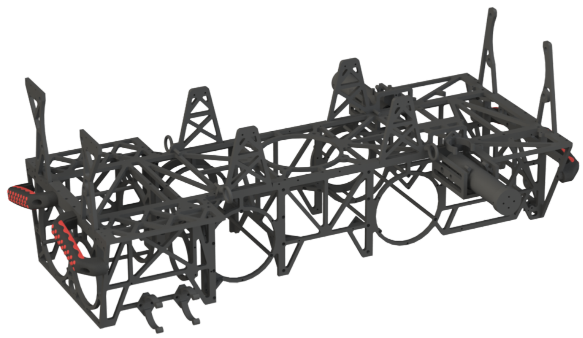


Figure 3: Artemis Frame

Artemis' frame was a direct successor to and improvement upon Thor's frame. It was also designed to be manufactured by waterjet. Artemis featured many experimental projects such as vector thrust and active ballast causing the frame to be more constrained than in the past, though the projects were never fully implemented on the vehicle. The frame also featured connections to the UHPV that were meant to make removing the hulls easier. Due to misalignment the attachments never made it on the vehicle and made it harder to remove the hulls. The frames hold down blocks were also not well supported and bent when the bolts were tightened. Additionally, there were many interferences leading to parts being hack sawed so the frame pieces fit together.

One of the major successes of Artemis' frame is the implementation of pipe clips to hold the swinging surge thrusters in the upright position. The design change combined with locking pins to keep the arms in place when in use made putting the vehicle in water easier. Another improvement was the handle placement as it was a lot more comfortable carrying the vehicle with angled handles. With the return to removable battery pods from the battery enclosures present on Argo/Thor, Artemis' frame featured delrin sliding rods with a bungee cord locking mechanism in order to easily remove and replace pods.

3.4 Castor (2018)

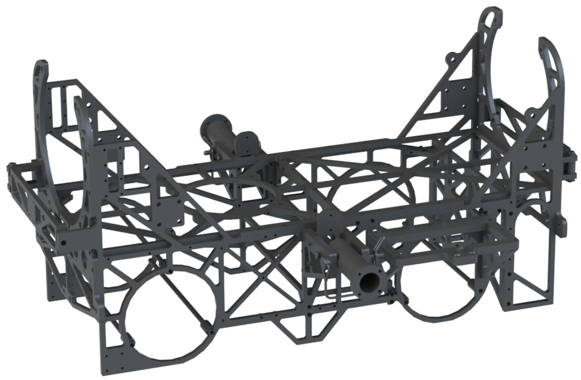


Figure 4: Castor Frame

Due to a massive reduction (approximately 8in) in UHPV length between Artemis and Castor, Castor's frame was in many ways an ultra-compact successor to Artemis' frame. With the major reduction in length, as well as temporary elimination of external camera enclosures on Castor (thanks to a clear fore endcap and repurposing of the midcap's DVL port), the packaging of components on Castor's frame was relatively dense; the end result of this packaging was a small and sleek submarine but at the cost of some serviceability and loss of space to add trim foam/weights. The frame also lacked space to mount manipulators due to the mid-design cycle revelation of a new recovery element. This resulted in the manipulators being mounted below the ground plane of Castor and required them to be removed whenever the vehicle was out of the water. Castor also featured the delrin rod battery pods mounts from Artemis, as well as a delrin mount for the valve enclosure which slid in vertically on the side of the vehicle.

Castor's frame featured further refinement of the swinging thruster wings pioneered on Thor, with the entire arm being a single machined piece to eliminate the alignment issues present on Artemis' wings. These wings featured the same tube clips as on Artemis, but interference with SEACON wires once the collision mitigation shrouds had beed added meant the clip could not be engaged. Additionally, Castor's frame removed the need to attach thrusters to the UHPV's endcaps by implementing horizontal swinging thruster mounts for the sway thrusters which move out of the way in order to remove the hulls.

3.5 Odysseus (2019)

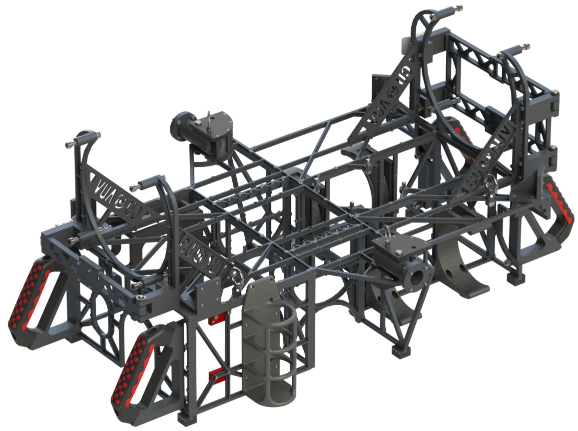


Figure 5: Odysseus Frame

Odysseus's frame aimed to improve upon Castor's frame's approach to packaging a shorter vehicle by drawing heavily upon the multi-width elements of Artemis' (2017) frame. Its specific objectives included adjusting to new mounting position requirements for the hydrophones enclosure as well as maximizing flexibility of enclosure mounting due to a delayed project timeline for new members. Characteristic features of the Odysseus frame included the swinging latches for the fore and aft thrusters, the surge wing assembly that allowed thrusters on the sides of the vehicle to be stowed away for transport, and sufficient room for the integration of projects that were finalized later in the design cycle. The Odysseus frame also utilized T-profile members last seen on Gemini thanks to manufacturing assistance from DATRON. Outsourcing manufacture of the frame, especially the holes on the faces of the frame pieces, greatly reduced manufacture time, but the added complexity of some frame pieces led to increased manufacture time. However, this added complexity improved accessibility for a compact and streamlined frame design.

4 High Level Description

Aurora's frame was designed primarily to accommodate major changes to past main vehicles. These changes include the addition of a second forward camera for stereo vision, the design of a longer UHPV with flipped fore and aft hulls relative to Odysseus, the addition of the new transmit enclosure, and the previously-undocumented need to center the DVL. Additionally, this design aims to build upon past vehicle designs while improving manufacturability and ease of use in certain areas, including by removing or improving upon the sway thruster latch systems, simplifying the surge thruster swings, and creating battery pod mounts that are functional for all members of the team.

The specific enclosure and component restrictions that informed enclosure placement and subsequent frame design are enumerated in Table 1 and Table 2 below. Specific priorities of Aurora's layout include mounting the hydrophones enclosure in the same orientation as on Atlas (formerly Leviathan (2020)) while protecting its elements in an unobstructive manner, placing the sensor boom enclosure in a quiet but accessible location, and keeping the width of the sub down. The frame was then designed to best accomplish these goals, with a varying width and surge thruster swings to keep enclosures and components both inside the width of the vehicle and accessible as well as careful attention to the most flexible parts of the midsection of the vehicle, checking interference for multiple moving parts. This layout is shown in the render of the full vehicle in Figure 6 below.

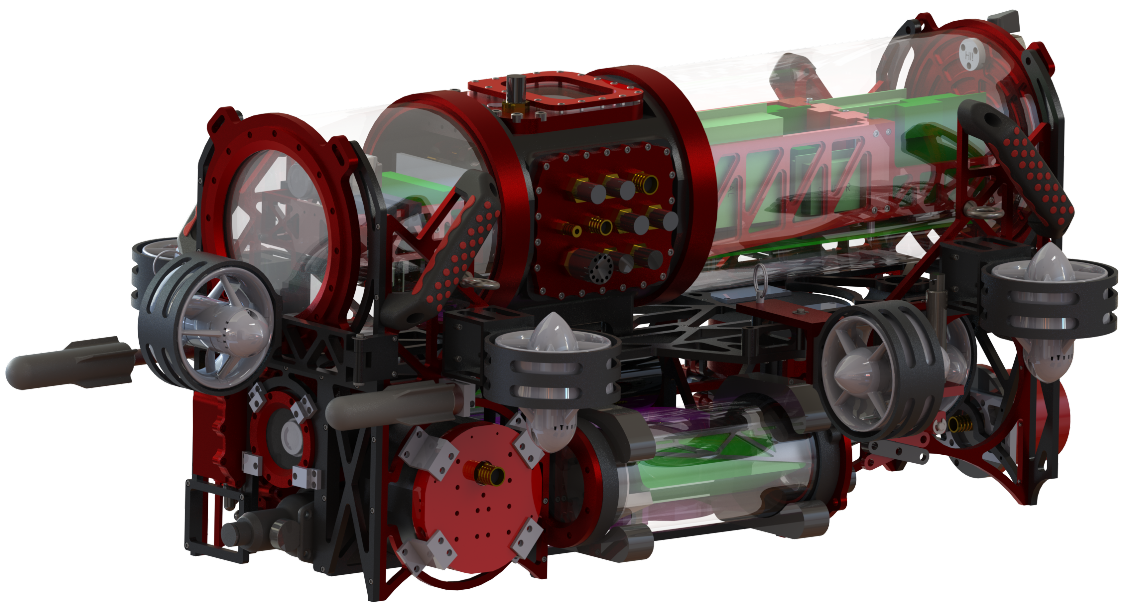


Figure 6: Aurora full vehicle assembly

Enclosure	Qty.	Placement Restrictions
UHPV	1	Centerline of vehicle, clearance for removing end caps and hulls, visibility of hulls, clearance around SEACON panels for bend radii
Hydrophones	1	In the same orientation as on Leviathan (2020) (front left of vehicle), elements pointing down but with clearance above the ground plane[1], as far from thrusters and other sources of noise as possible, trigger element in proper orientation relative to front of vehicle
Sensor Boom	1	Away from thrusters and other sources of electrical noise, aligned to main axes of vehicle
Forward Cameras	2	Front of vehicle, at centerline of vehicle, viewcones unobstructed, cameras at the same distance from the fore end of the vehicle for stereo vision
Downward Camera	1	Bottom of vehicle, centerline of vehicle, ideally at the center of the vehicle, viewcone unobstructed, clearance above ground plane
Killswitch	1	Aft of vehicle and easily accessible
Valve Enclosure	1	Anywhere the push-to-connects are easily accessible, must be easily removable
Transmit	1	Placed anywhere[2]
Battery Pods	2	Anywhere provided they are easily removable

Table 1: Enclosures List

[1] **The ground plane** is the very bottom plane of the vehicle, or the plane on which the vehicle will rest. Vehicles are normally designed to touch the ground at no more than 8 points to stay level even if obstructed, and the frame is designed to keep enclosures and components well above this plane to prevent damage from objects on the ground.

[2] **Transmit placement** was restricted less this year, as the transducer is tethered to, not sealed inside, the enclosure for testing. The flexibility of the transducer outside of the enclosure removes the need for careful placement, but the enclosure is normally placed such that waves are unobstructed in front of, behind, and on top of the enclosure.

Component	Qty.	Placement Restrictions
DVL	1	Bottom of vehicle, unobstructed sensing cone at center of vehicle, clearance above ground plane
Handles	4	Fore and aft ends of vehicle, symmetric about midplane of vehicle, angled as to be ergonomic
Torpedo Tubes	2	Fore end of vehicle, near each other, close to fore camera, far enough from fore camera to prevent obstruction of view cone, including with bubbles
Dropper Tubes	2	Bottom of vehicle, near each other, close to downward camera, far enough from fore camera and DVL to prevent obstruction of view and sensing cones, including with bubbles
Manipulators	2	Near downward camera, close to but with large clearance above the ground plane
Thrusters	8	Preferably coplanar about the center of mass of the vehicle, symmetry about the center plane of the vehicle (for depth thrusters), away from where SEACON protrude from the UHPV when in use (for surge thrusters)
Air Tank	1	Easily removable for refilling, near the valve enclosure
Eye Bolts	4	Spread out to the far corners of the vehicle, not obstructed after assembly and cable managment

Table 2: Non-Enclosure Components List

4.1 Plates

The plates make up the main structure of the frame, providing mounting space for all enclosures, protecting them from damage, and supporting their weight.

4.1.1 Top Plate

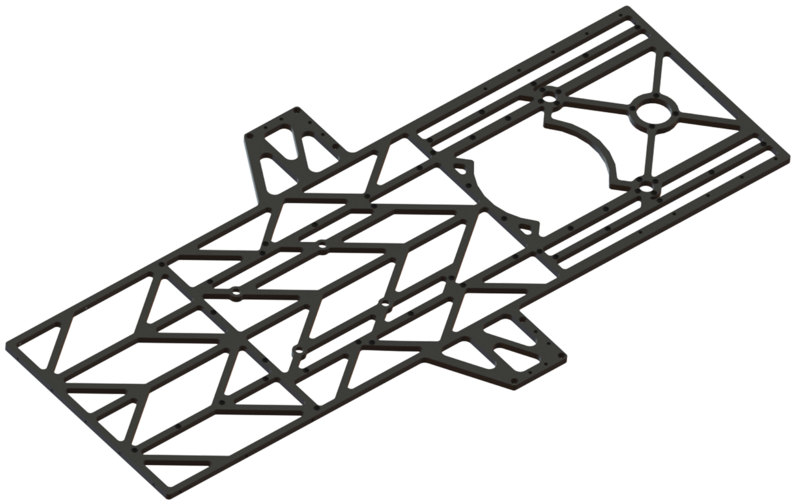


Figure 7: Top plate

The top plate interfaces directly with every plate on Aurora with top- and side-facing mounting holes, with additional holes on the front and back faces to interface with the fore and aft plates, if possible[3]. The top plate serves to center the frame around the UHPV. In addition to the UHPV's four mounting holes, the top plate has mounting holes for all enclosures and components that lie directly and completely underneath the UHPV. From fore to aft, this includes holes for sensor boom mounting, the downcam brackets, torpedoes, and the aft sway thruster. The top plate also features large cutouts for weight savings, placed to improve visibility and accessibility as well as to serve more specific purposes, such as leaving room for hydrophones SEACON at the front of the sub. Another primary feature of the top plate is the surge thruster wings, which serve to mount the surge thruster wing assemblies, adapted from Odysseus and described in Section 4.1.2. When reasonable but undesirable deflection of these wings was found in simulations, weight savings on the wings were reduced to mitigate deflection.

[3]**Front and back mounting holes** that connect the fore and aft plates to the top plate are optional and dependent on the feasibility of the necessary machining setup. This is described further in Section 6.

4.1.2 Fore Plate

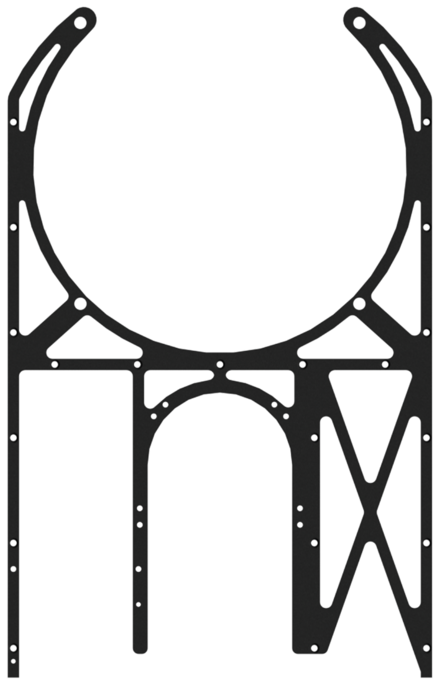
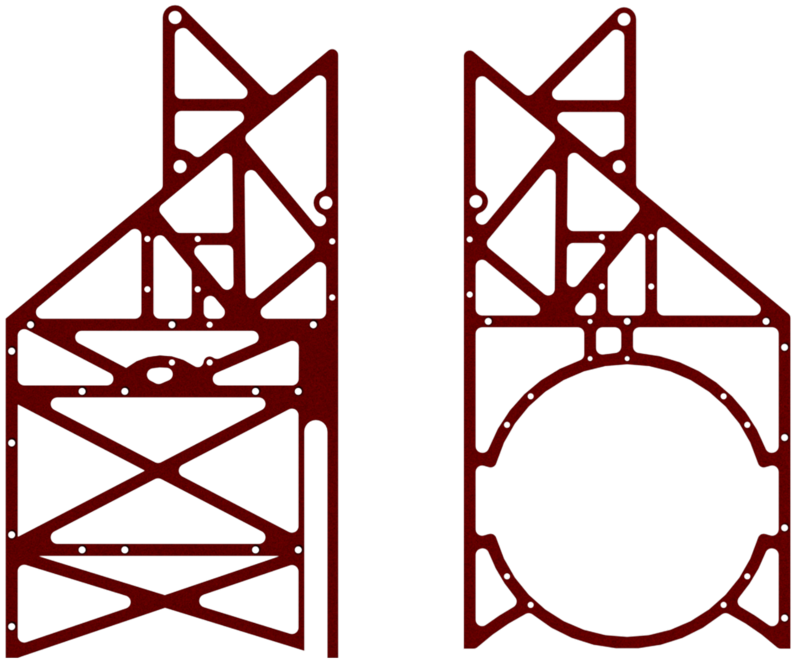


Figure 8: Fore plate

The fore plate serves as a primary structural member of the frame, further constraining the side plates to the top plate as well as providing additional mounting for the UHPV. The only other enclosure that mounts to the fore plate is the foreward camera, with holes for mounting brackets near the center. The fore plate also serves to protect enclosures at the front of the vehicle from damage, with space for a hydrophones bracket that obstructs the hydrophones elements from damage as well as cutouts that enclose the valve enclosure. The large slots at the front leaves ample space for enclosures to slide in from the front or bottom as well as allowing both the forecam and the paintball tank to be placed at the very front of the vehicle. The fore plate, along with the fore side plates, also has one of the contact points between the vehicle and the ground plane on each side.

4.1.3 Fore Side Plates

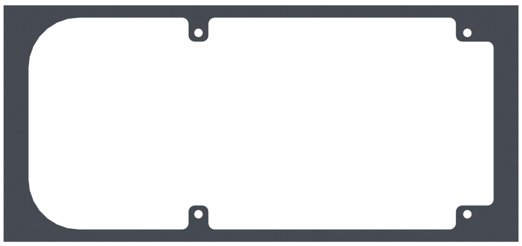


(a) Fore starboard side plate (b) Fore port side plate

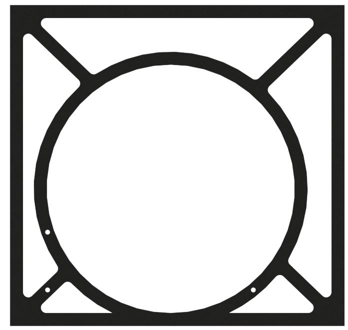
Figure 9: Fore side plates

The fore side plates each mount six enclosures or components: a torpedo, a depth thruster, an eye bolt, a handle, the fore sway thruster swing assembly, and either the valve enclosure (port side) or the hydrophones enclosure (starboard side). As a result, these plates has smaller weight savings and more holes that interface with other parts of the frame's structure to prevent deflection or yielding. While they eye bolt, handle, and swing assembly mount directly to the plates, the depth thruster, torpedo, and valve or hydrophones enclosure all mount with brackets or blocks described later. The fore port side plate leaves room for the valve enclosure, including its large side latches, to slide in from the side. The fore starboard side plate was designed to mount both the Kraken and Leviathan hydrophones enclosure (2020) as well as the Artemis and Apollo hydrophones enclosure (2017) due to ongoing testing of the new enclosure. While the new enclosure can slide in easily from the front of the vehicle when the hydrophones bracket is removed, the fore starboard side plate has a long slot that allows an extruding SEACON connector on the old enclosure to slide up from the bottom while keeping the fore plate intact and interfacing with the fore starboard side plate.

4.1.4 Enclosure Mounting Plates



(a) DVL mounting plate

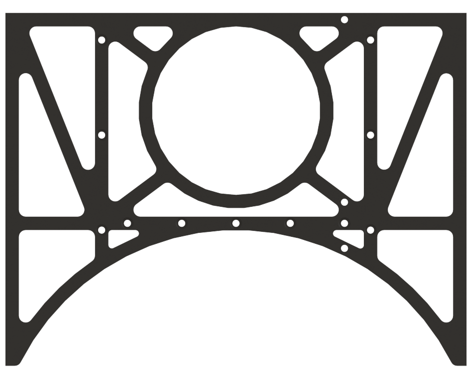


(b) Valve enclosure ring plate

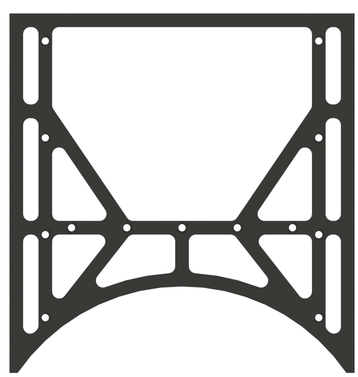
Figure 10: Enclosure Mounting Plates

The valve enclosure ring and DVL plate do not serve as primary structural members of the frame; they are each well above the ground plane and primarily serve to mount a specific enclosure. The Valve Enclosure Ring provides additional security for the somewhat heavy valve enclosure to prevent it from being cantilevered off of four small brackets. The ring in this plate matches the diameter of the lower valve enclosure, as it no longer has to account for large latches. This plate also provides holes for standoffs for the paintball tank mount. The DVL plate was adapted from Odysseus to fit the dimensions of Aurora's frame but is otherwise identical. It has four mounting holes for the DVL and peripheral mounting holes to the frame, mounting the DVL well above the ground plane to protect the very expensive and valuable enclosure from any damage.

4.1.5 Mid Plates



(a) Fore mid plate



(b) Aft mid plate

Figure 11: Mid plates

The two mid plates serve to provide mounting for the DVL plate and provide additional structure for the side battery plates, described in Section 4.1.6. In doing so, they also change the width of the vehicle as necessary to mount the batteries and manipulators in a streamlined way. The width of the aft mid plate was designed to expand the aft width of the sub past that enclosed by the battery plates, leaving room for the downcam and droppers while allowing the handles and SEACON on the batteries to extrude past the length of their mounting plates. The fore mid plate was designed to interface with the fore side plates (Section 4.1.3) at the widest parts of the top plate as well as provide flexibility for the lower forecam or the lower forecam's SEACON to move back into the midsection of the frame, if necessary. Both mid plates serve as additional contact points between the vehicle and the ground.

4.1.6 Battery Plates

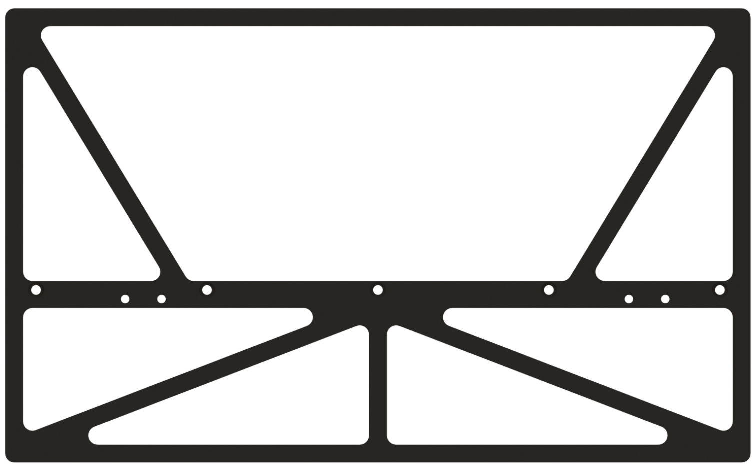


Figure 12: Starboard battery plate

The battery plates further constrain the fore and aft sections of the vehicle's frame to each other as well as provide mounting for the DVL plate and the battery mounts (Section 4.3). These plates feature large cutouts at the top to allow the sensor boom to be removed through either side of the vehicle when the batteries are not mounted. The placement of these plates in the frame is based on the width of the DVL plate and allows the batteries to be housed nearly completely inside the frame.

4.1.7 Aft Side Plates

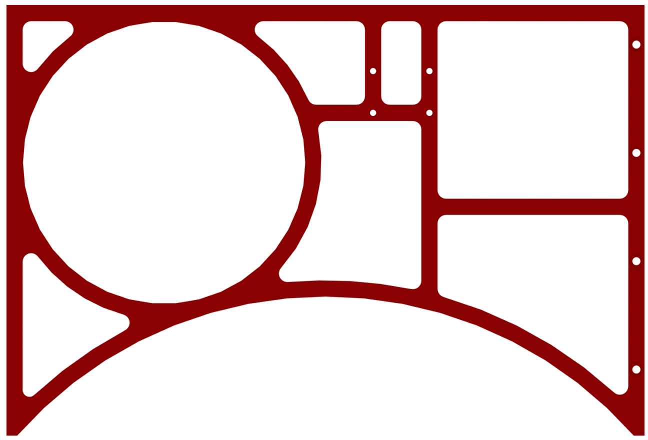
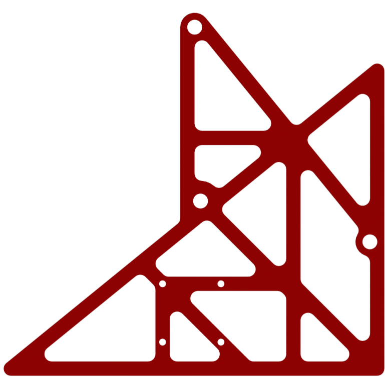


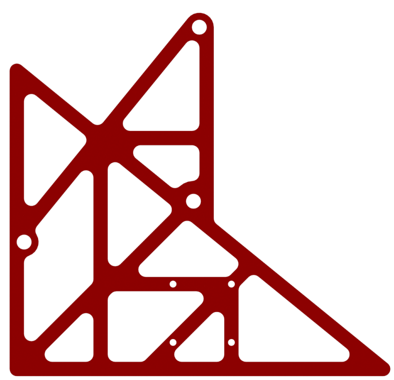
Figure 13: Port aft side plate

The aft side plates provide mounting for the manipulators, cutouts to facilitate downcam SEACON routing, and a clear path for the aft sway thruster. The arcs on the aft side plates converge with those on the aft plate and the aft mid plate at four points, acting as half of the contact points between the vehicle and the ground. Unlike the fore side plates, the aft side plates make up only half the height of the sub due to the width constraints placed by hardware on the end of the battery pods and the subsequent placement of these plates directly under the top plate.

4.1.8 Aft Triangles



(a) Port aft triangle



(b) Starboard aft triangle

Figure 14: Aft triangle plates

The aft triangles serve as the equivalent top half of the aft side plates. Like the fore side plates, these identical plates mount eye bolts, handles, and thrusters in the same fashion as at the fore end of the sub. They also constrain deflection on the top of the aft plate by connecting the UHPV mounting ring to the top plate.

4.1.9 Aft Plate

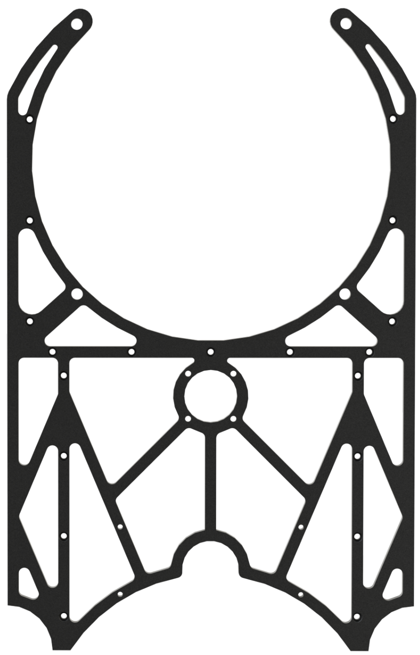


Figure 15: Aft plate

The aft plate provides mounting holes for the transmit enclosure killswitch, holes with which the UHPV end cap can interface, room for transmit SEACON, and contact points with the ground. Like the fore plate, it interfaces directly with its corresponding side plates and has optional mounting holes for the top plate.

4.2 Thruster Mounting

4.2.1 Fore Sway Thruster Swing

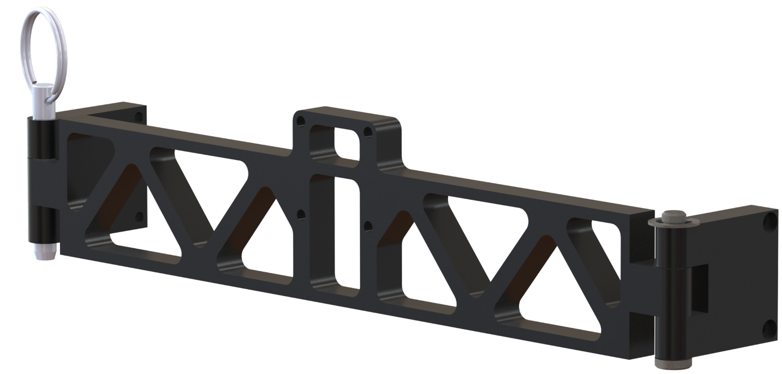


Figure 16: Fore sway thruster swing assembly

The mounting swing for the fore sway thruster allows the fore sway thruster to sit in between the viewcones of the two forecams while allowing ease of access to the fore end cap of the UHPV. This assembly is quite similar to the latch mechanisms found on Odysseus; however, due to tolerance and manufacturing issues encountered with the latches used on Odysseus, a removable and a non-removable pin were opted for instead. The assembly features two mounts that interface with the fore side plates and have sufficient tolerance to allow the swing to move freely, a quick-release self-locking pin from McMaster, a non-removable pin with a retaining ring, and a swing with large weight savings and mounting holes at the center for the fore sway thruster.

4.2.2 Surge Thruster Swings

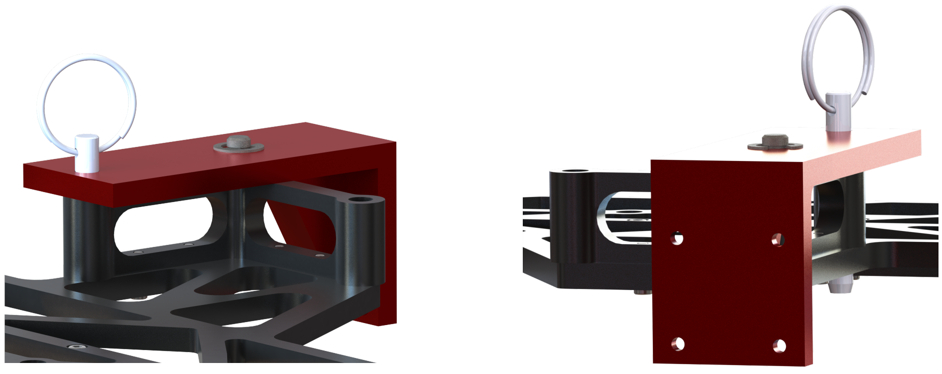


Figure 17: Two views of surge thruster swing assembly mounted to top plate of frame

Aurora's surge thruster swings aim to simplify the surge thruster swings of years past by using fewer and more easily manufacturable parts. The assembly involves a set of standoffs merged together with holes to mount to the top plate as well as a bracket that connects with a quick-release and non-removable pin to the standoffs and frame. This assembly was dimensioned specifically to clear a path for the surge thrusters when in their extended position while leaving ample room for battery pod removal when in their inwards position.

4.2.3 Thruster Blocks

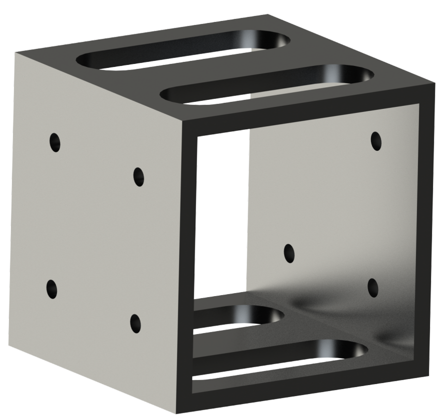


Figure 18: Depth thruster blocks

The thruster blocks, adapted from Ajax, are the final parts created for the purpose of thruster mounting. Manufactured from aluminum tube stock, these blocks allow the depth thrusters to clear parts of the frame in which they would otherwise be obstructed by enclosures, SEACON, or plates.

4.3 Battery Pod Mounting

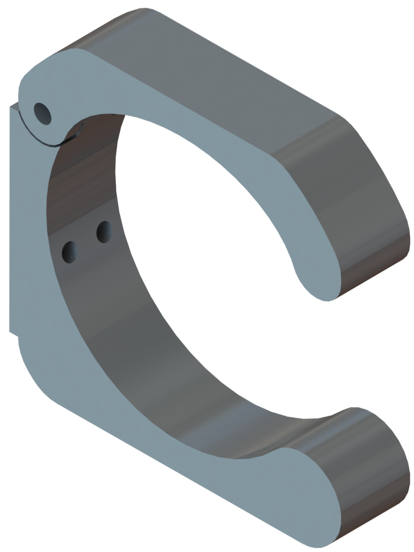


Figure 19: Battery pod mounting

As with the fore sway and surge thruster mounting, Aurora's battery pod mounting aims to improve upon previous designs. In response to difficulties removing battery pods from Odysseus's press-fit-based battery pod mount design, Aurora's redesign of battery pod mounting splits the mount into two parts, using a pin to connect the two parts while allowing rotation and a bungee cord to hold the top piece of the battery pod mount down when a battery pod is in place. Two of these mounts are featured on each side of the vehicle, spaced apart such that the length between the end caps of the battery pods themselves constrain their motion and such that the sensor boom can still be removed through the sides of the vehicle when the batteries are not in place. These parts will be 3D printed and iterated upon as necessary.

5 Current Status

The design of the frame is complete, and simulations have been run (Section A) to verify the structural integrity of the frame. Some mounting brackets for the new hydrophones enclosure have yet to be designed, but the old hydrophones enclosure is most likely to be used and one bracket for the new hydrophones enclosure has been placed to verify the enclosure will fit with the frame. All parts to be manufactured by DATRON will be sent in sometime later in the year, and modifications to the parts, such as additional holes drilled and tapped, will be made once they are received. Manufacture of some of the brackets that help enclosures and components interface with the frame may be manufactured as early as at the end of this semester. Additional simulations may be run for peace of mind before certain parts are manufactured; for example, the kill switch activation load case examined in previous frame documentation may be run before the plates are sent to DATRON, and more realistic loading conditions may be tested on thruster mounting assemblies and parts; however, large factors of safety on all simulations run thus far suggest no changes will be made to the design. Finally, the battery pod mounting will need to be developed further, including by sending iterations to the RPL for printing and testing as well as by finding appropriate off-the-shelf components, such as pins and hooks, with which the assembly can be made completely functional.

6 Future Improvements

Because the frame has just been designed and all of the parts have yet to be manufactured, it is difficult to assess where it could improve. The only known issue thus far is the placement of the fore sway thruster such that it interferes with both forecam viewcones to some extent, but the cameras are nearly as far forward and the thruster nearly as far back as possible, so the interference has been minimized. There are, however, some considerations I would have made earlier if I were to redesign, including thinking more about manufacturability and prioritizing handle placement in the same way other enclosure requirements were prioritized.

Some changes may be made to the proposed design in this document due to manufacturability constraints, but none will affect the functionality of the vehicle's frame. Due to the large 26.5 in length of Aurora's top plate, the machines in the Emerson machine shop may not be large enough to support creating the holes on the fore and aft faces of the top plate, and the frame plate manufacturer, DATRON, only creates top-facing features. As a result, the holes that connect the fore and aft plates to the top plate directly may not be present; however, simulations were run without the holes present, and the factor of safety on the frame for both the eye bolts simulation and the handles simulation were sufficiently high. Additionally, towards the end of the design cycle, some smaller parts, namely for the surge thruster swings, were designed without ease of manufacturability in mind. While these may be parts to machine for fun towards the end of this semester, they may also be modified to prioritize saving time over aesthetics, depending on when and by whom they are manufactured.

If I were to redesign, I also would have prioritized handle placement more. While I specifically noted handle placement in my PPDR, as I received stricter requirements and more feedback on enclosure placement as well as recognized the complexity of my original design, I decided handles were not a priority and waited to place them until I felt comfortable with the remainder of my enclosure layout. As a result, I feel the handle placement is likely not the most comfortable or ergonomic, and were I to redesign, I would not leave handle placement as an afterthought. Additionally, this year, an experimental project focused on designing a better way to move and place the sub, and I failed to consider how that project would interface with my frame. While the project should be adaptable to different frame versions, because it is in its early stages, I should have considered its placement more to ensure a prototype could be tested.

The final problem I anticipate is accessibility to enclosures directly under the UHPV. Not having interacted with any of our subs very much due to COVID and because it was difficult to judge accessibility from a SolidWorks file alone, I am not sure how easily the mounting holes to some of the enclosures can be reached, though I tried to move them as far out to the sides as possible. Once the frame is manufactured, this section will be updated to reflect whether that was a problem.

Appendices

A Finite Element Analysis

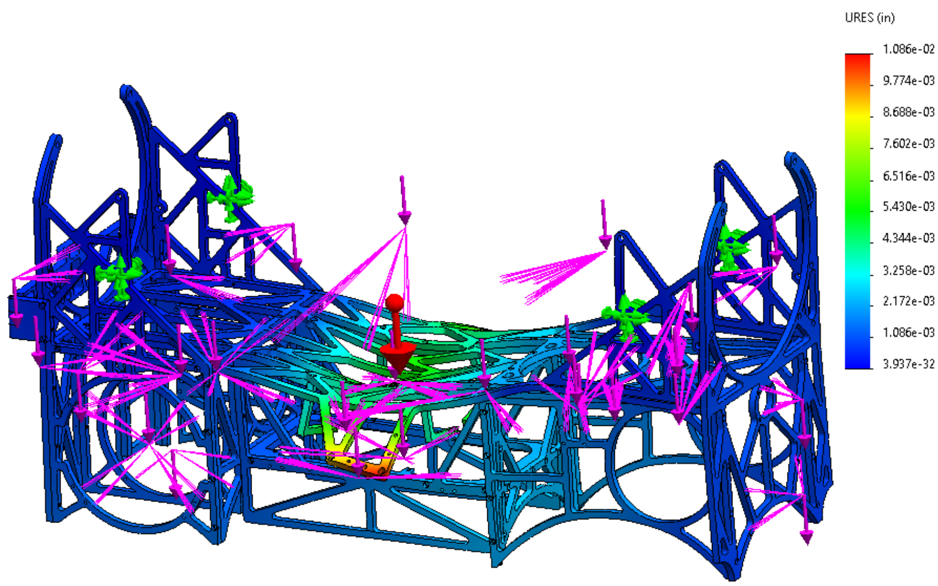
To ensure the frame can support the weight of the enclosures and components as well as the stresses of regular use, multiple simulations were run to assess the stress and deflection on the frame and some of its parts. The results of these simulations are summarized in Table 3 below.

Load Case	**Max. Stress (MPa)**	**Max. Deformation (0.001")**	**Factor of Safety (Yield)**
Crane Lift	41.30	10.86	3.63
Handle Lift	41.51	10.46	3.61
Thruster Weight - Block	3.029	6.704	49.5
Thruster Weight - Swing	3.769	4.977	39.7

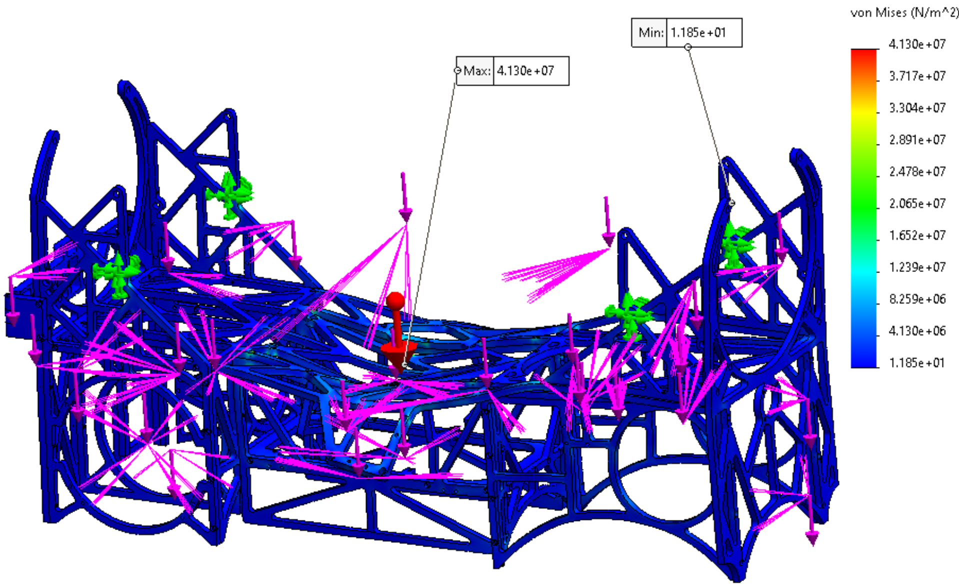
Table 3: FEA Load Cases and Results

A.1 Eye Bolt Simulation

When the vehicle is raised and lowered into the water at competition, the four eye bolts and the plates to which they are connected must support the weight of the vehicle. To simulate these loading conditions, remote forces were placed at the centers of mass of each of the enclosures and components and loaded onto the mounting holes for their respective components. Additionally, a gravity load was applied to the frame itself. Then, the four eye bolt holes were fixed, and the stress and deflection were observed. It was especially important to run this simulation and the following simulation to test whether the fore and aft side plates were sufficiently constrained to prevent large deflection.



(a) Deflection results of eye bolts simulation

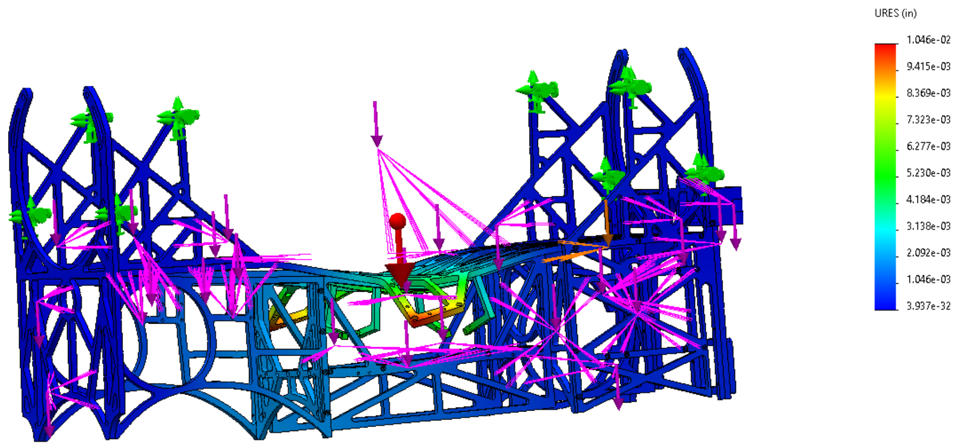


(b) Stress results of eye bolts simulation

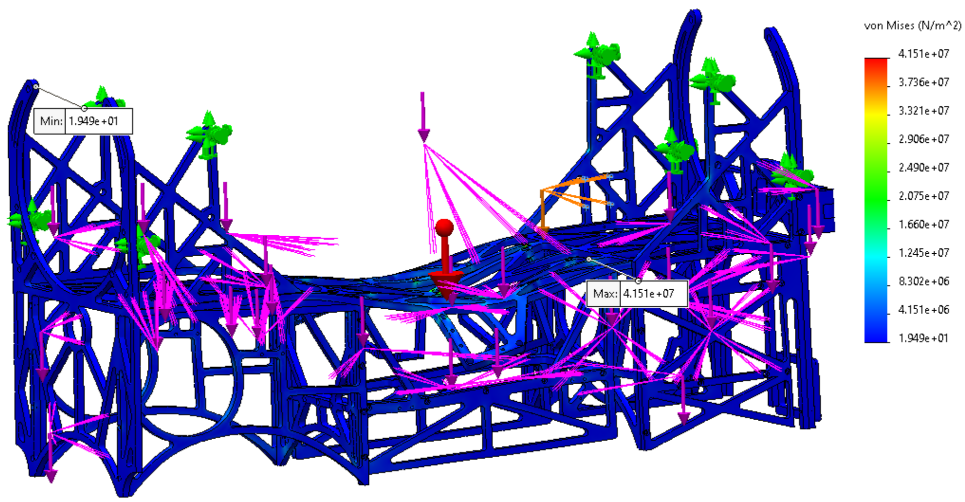
Figure 20: Eye bolt simulation results

A.2 Handles Simulation

For the handles simulation, the same forces as in the eye bolts simulation were applied; this time, the mounting holes for the handles were fixed in place. The results of these simulations are shown below.



(a) Deflection results of handles simulation

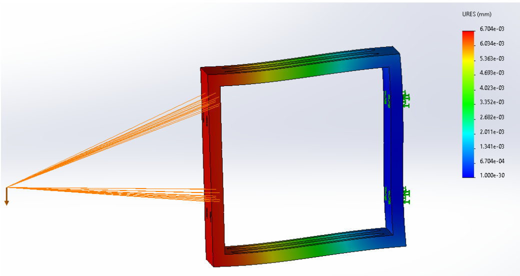


(b) Stress results of handles simulation

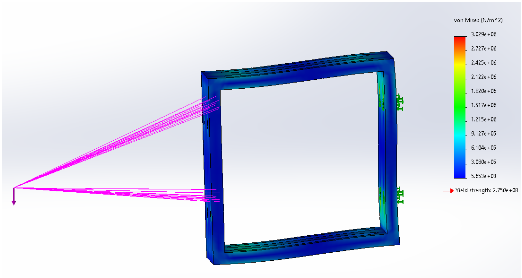
Figure 21: Handles simulation results

A.3 Thruster Mounting Simulations

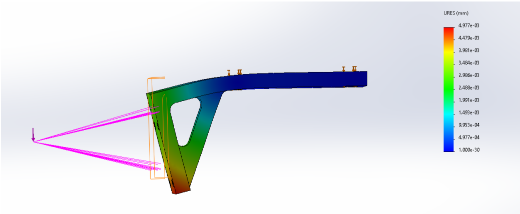
Simple simulations were run on the thruster blocks and surge thruster swings, two parts with thin features. A remote load at the center of mass of a thruster was applied to the thruster mounting holes on the surge thruster bracket and the depth thruster blocks. While these loading cases only hold for static cases, not for when the thrusters are running and applying additional forces on their mounts, the factor of safety for each case was so high and the deflection so low that there is no reason to believe more realistic loading conditions would cause significantly more adverse results.



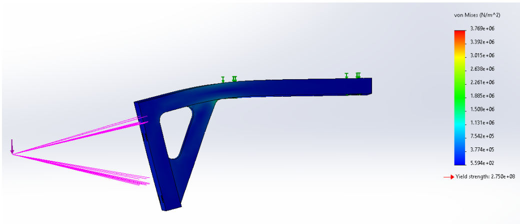
(a) Deflection of depth thruster blocks



(b) Stress on depth thruster blocks



(c) Deflection of surge thruster brackets



(d) Stress on surge thruster brackets

Figure 22: Thruster mounting simulation results