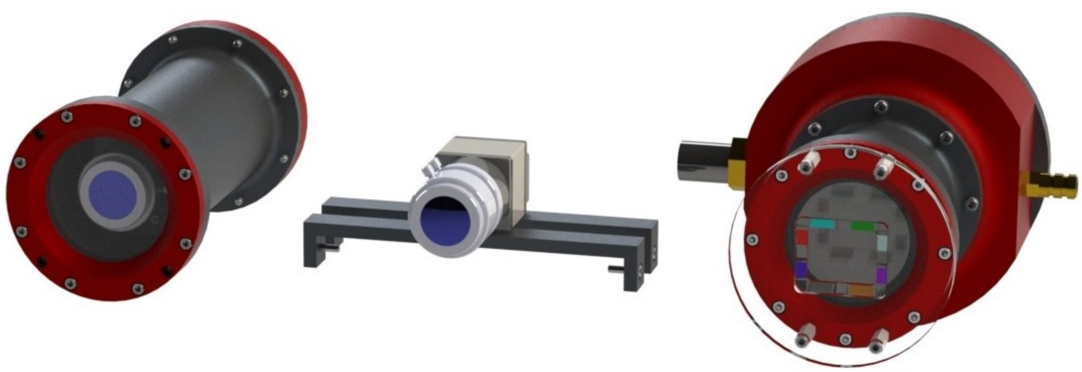
Cornell University Autonomous Underwater Vehicle Team

Spring 2021

Camera Enclosures



Technical Report

Michael Liang (ml2226)

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Contents

1 Abstract

The camera enclosures must securely seal and enclose the camera-lens combination to prevent external fluid exposure. In particular, the camera-lens combinations, camera enclosures, and color palette must integrate methods of mounting to the body or frame. Respectively, the two forward facing and downward facing camera-lens combinations provide for a stereoscopic perspective and a distinct view cone direction.

An Imaging Development Systems (IDS) UI-5140CP camera is combined with a Navitar NMV-4WA lens for the stereoscopic forward facing camera combination on the autonomous underwater vehicle (AUV) Aurora. Notably, the forward facing camera-lens combination located in the UHPV mounts to the fore racks whereas the partnering forward facing camera enclosure mounts to Aurora' frame at the forward facing flange.

On the other hand, the Aurora' downward facing camera — (IDS) UI-5250CP — is combined with a Kowa LM3NCM lens. Particularly, the downward facing enclosure's endcap mounts directly to Aurora' frame. Moreover, both external enclosure's camera-lens combination uses a bracket mounted to the endcaps to provide for a stable viewing environment.

2 Design Requirements

2.1 Constraints

- Fit the camera-lens combination
- Remain watertight at appropriate depths
- Have view cone unobstructed
- Mount onto frame and seal independently
- Stereo-forward cameras lie on a co-linear vertical plane

2.2 Objectives

- Stabilize and protect the camera-lens combination
- Easy to assemble and/or disassemble
- Minimize space and weight
- Leave adequate room for connectors and cables
- Easy to machine or reproduce
- Minimize length of downward camera enclosures
- Utilize 3D printed parts if feasible

3 Previous Designs

3.1 Killick (2011)

Figure 1: Killick Camera Enclosure

Prior to Killick (2011-2012), Cornell AUVs have featured external camera enclosures in the form of fully-external camera hulls which sealed independently and mounted to the frame of the AUV. Killsick introduced both endcap-mounted and Upper Hull Pressure Vessel (UHPV)-mounted camera enclosures for both the forward and downward cameras. Most notably, the forward and downward camera enclosures (Figure 1) implemented in Killick's design are identical and both use O-rings to create face seals to mount to their respective sealing surfaces. The downward camera enclosure mounts to the bottom of the UHPV, while the forward camera mounts to the endcap of the UHPV.

3.2 Gemini (2015)

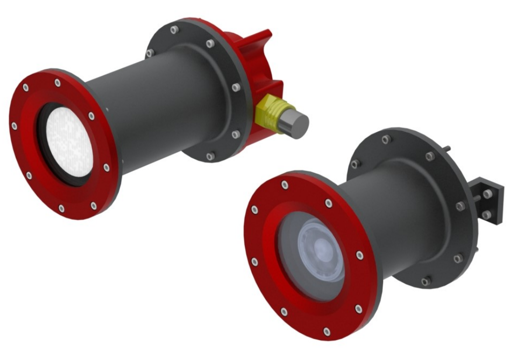
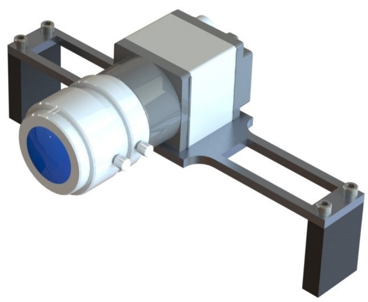


Figure 2: Gemini Camera Enclosures

Gemini's forward camera enclosures (Figure 2 on right) used endcap mounted hulls as first used in Killick. The Gemini camera enclosures largely focused on maintaining effective sealing methods and retaining the general model of Killick's designs. Gemini was also the latest AUV that attempted stereoscopic forward vision, and switched to 100 series o-rings for more reliable seals. Gemini reverted back to a fully external downward camera enclosure (Figure 2 on left) to account for its UHPV design and the shorter frame. Connectors were also made to extend sideways in Gemnini's downward enclosure design, effectively reducing enclosure height but thickening the rear endcap.

3.3 Castor (2018)



(a) Forward Camera-Lens Combination

(b) Downward Camera Enclosure

Figure 3: Castor Camera Enclosures

The forward camera-lens combination (Figure 5 (a)) of the Castor was the first vehicle in AUV to utilize the electronic racks as a bracket mounting surface. With this design, the forward camera-lens combination in the UHPV reduces the need for an external enclosure. The two bracket standoff supports attached to the racks serve as elevation, lifting the camera above and giving clearance from the Jetson TX2 Computer. Most notably, the weight-saving design of the bracket allows connectors to be freely plugged into the Jetson computer but also mounts the camera in the desired location. Consequently, the camera mounting bracket is thin and may need to be changed to accommodate different lenses or cameras, and therefore is a laser-cut piece.

The downward camera enclosure (Figure 5 (b)) for the vehicle Castor employed a design very different than that of prior AUV's. Instead of using an endcap, this design implemented a second hull, used for mounting the bracket assembly while also easing machinability and accessibility to the camera-lens combination. In particular, Castor's downward camera enclosure followed a fairly conventional design, but had its enclosure sealed to the UHPV with a bore seal. Another new implementation was the newly designed bulkhead which was 3D printed with ABS plastic and was designed to tightly fit around the camera and bracket, giving additional stability to the camera bracket assembly.

3.4 Odysseus (2019)

Figure 4: Odysseus Camera Enclosures

The most notable features of the camera enclosures of the Odysseus was the removal of the bulkhead and the placement of the SEACON connectors on the side of the endcap on the downward camera enclosure. In particular, the larger cup-like shape of the downward camera enclosure's (Figure 4 on right) endcap gives more room for the wiring inside.

3.5 Leviathan (2020)

Figure 5: Leviathan Camera Enclosures

Leviathan's forward camera enclosure (Figure 7 on left) used the back face of the hull to attach to the UHPV. On the other hand, Leviathan's downward camera enclosure emphasized a larger endcap primarily to ease the machinability of the hull. Along with this, the SEACON connectors were located on the back-plane of the endcap. Most notably, the bracket-assemblies of Leviathan implemented bulkheads that encompassed the entirely of the camera.

4 High Level Description

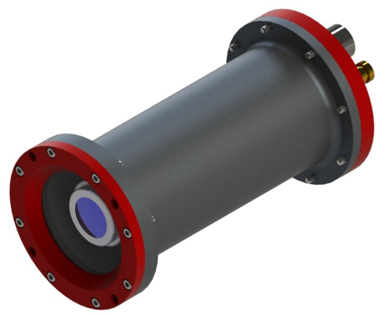


Figure 6: Aurora External Forward Camera Enclosure

The Aurora external forward camera enclosure (Figure 6) has four major components: the flange, the hull, the bracket, and the endcap. The hull of the external forward enclosure serves as the casing for the bracket (L-shaped) and will be mounted to the endcap with two #4-40 screws. Attached to the hull are the endcap and the flange effectively sealing the enclosure. In particular, the endcap has attachments for the SEACON connectors while in between the flange and the hull is the viewport: the borosilicate glass disk. The UI-5140CP camera attaches to the bracket with M3 screws along with its Navitar NMV-4WA lens.

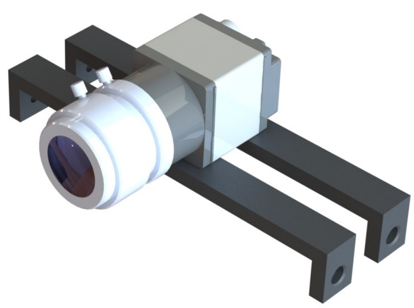


Figure 7: Aurora Internal Forward Camera-Lens Combination

The Aurora internal forward camera-lens combination (Figure 7) has one main component: a bridge-shaped bracket. The two bridge-shaped bracket that mounts to the aft racks with #4-40 screws in the UHPV has the UI-5140CP camera along with its Navitar NMV-4WA lens is attached using 4 M3 screws. With both the forward facing cameras on the same vertical plane, they combine to create stereo-vision for the AUV.

Figure 8: Aurora External Downward Camera Enclosure

The Aurora external downward camera enclosure (Figure 8) has five major components: the flange, the hull, the bracket, the endcap hull, and the endcap. The hull of the external downward enclosure serves as the casing for the bracket (L-shaped) and will be mounted to the endcap with two #4-40 screws. Attached to the hull are the endcap and the flange effectively sealing the enclosure. In particular, the endcap has attachments for the SEA-CON connectors while in between the flange and the hull, is the viewport: the borosilicate glass disk. The UI-5250CP camera attaches to the bracket with M3 screws along with the Kowa LM3NCM lens. Most notably, male-female threaded standoffs are used to attach the enclosure to the underwater color perception palette.

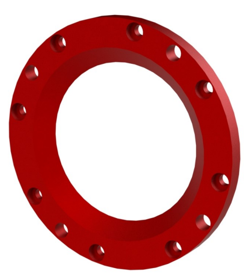
4.1 Aurora External Forward Camera External Enclosure

4.1.1 Hull

Figure 9: Aurora External Forward Camera Enclosure Hull

The hull (Figure 9) is made of 6061-T6 Aluminum and is similar in design to previous forward camera hull designs. The enclosure's length is 5.1" giving about 1.8" of space for the wires and the rest for the camera-lens combination. The enclosure's inner diameter is 2.0", which is smaller than the previous designs because the bulkhead encompasses the lens and not the camera. The thickness of the hull's cylindrical base is 0.1", making the outer diameter of the cylinder 2.2". As a result of the smaller inner diameter, the outer diameter of the front and back faces is 3.0". There are three size 139 O-ring grooves with a 0.125" inset for the viewport, flange, and the endcap. In addition, eight #4-40 tapped holes are on both the front and back faces of the hull for the face seal to the flange and endcap, respectively. Another four #4 clearance holes on the front of the hull is used to attach to the frame of the AUV.

4.1.2 Flange and Endcap



(a) Flange

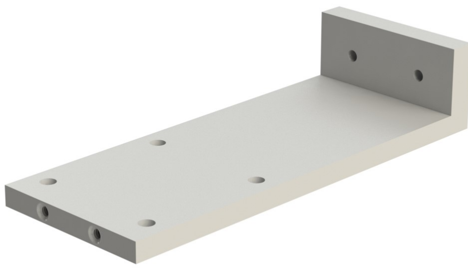
(b) Endcap

Figure 10: Aurora External Forward Camera Enclosure Flange and Endcap

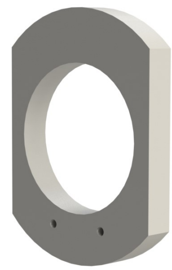
The flange (Figure 10 (a)) is made out of 6061-T6 Aluminum. The back face of the flange has a size 139 O-ring groove, and the outer diameter is 3", which is consistent with that of the hull. Eight #4-40 counter-bored screw holes are spaced in a circular pattern on the front face of the flange and align with the pattern of the holes on the front face of the hull to ensure that the enclosure is watertight. Its overall thickness is 0.2", and there is a 0.25" thick chamfer at a 45 degree angle.

The endcap (Figure 10 (b)) is made out of 6061-T6 Aluminum. The endcap will be directly face sealed onto the hull and will have a diameter of 3", which is consistent with that of the hull. Eight #4-40 counter-bored screw holes are spaced in a circular pattern on the back face of the endcap and are aligned with the pattern of the holes on the back face of the hull to ensure that the enclosure is watertight. Its overall thickness is 0.3" and there are two SEACON connectors: an MCBH-8 and a HUMG-2 that are face-sealed and screwed with 5/16" and 7/16" washers and 5/16"-24 and 7/16"-20 nuts. Furthermore, there are two #4-40 threaded holes with a depth of 0.15" that allow for the attachment of the bracket.

4.1.3 Bracket and Bulkhead



(a) Bracket



(b) Bulkhead

Figure 11: Aurora External Forward Camera Enclosure Bracket and Bulkhead

The bracket (Figure 11 (a)) is an L-shaped cantilever, made of 3D-printed ABS plastic that supports the camera-lens combination within the hull of the enclosure. The bracket is 0.65" tall, 3.27" long, and is 0.15" thick. The UI-5140CP camera mounts from four M2.5 counterbored screw holes on the bracket. The two #4 clearance holes on the leg of the bracket mounts to the two #4-40 tapped holes on the endcap. Most notably, the two #2-56 heat-set inserts allows the ABS plastic bracket to securely attach to the bulkhead with screws.

The bulkhead (Figure 11 (b)) is a 3D-printed support mechanism using ABS plastic to ensure that the camera, lens, and bracket remain stable whenever the AUV is in motion or operating the cameras. It is different from previous designs in which it encompasses the lens rather than the body of the camera and allows the hull diameter to be minimized. The bulkhead's outer diameter is 2.0" and its thickness is 0.236" (6 mm). Furthermore, there are two #2 clearance holes for the #2-56 socket head cap screws that screws to the heat-set inserts soldered into the bracket.

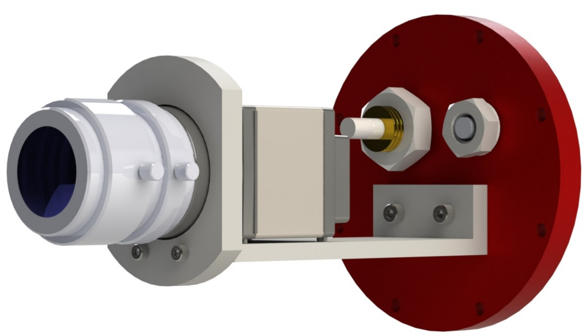


Figure 12: Aurora External Forward Enclosure Bracket Assembly

4.1.4 Viewport

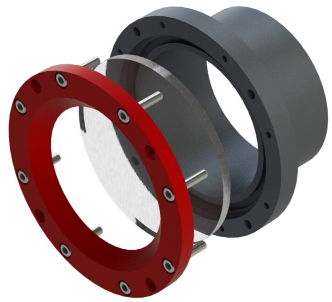


Figure 13: Aurora External Forward Camera Enclosure Sectioned Viewport

The viewport (Figure 13) is a 0.125” x 2.5” diameter disk of borosilicate glass that is secured between the flange and the front face of the hull. Two size 139 O-rings are on both sides of the viewport to ensure sealing of the enclosure. With the help of the viewport, the viewcone is unobstructed not only maximizing the view angle, allowing the camera to use its full range of visibility.

4.2 Aurora Internal Forward Camera-Lens Combination

4.2.1 Bracket

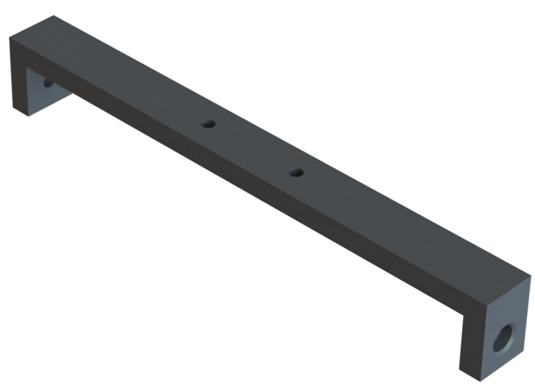


Figure 14: Aurora Internal Camera-Lens Combination Bracket

The bridge-shaped bracket (Figure 14) is made of 6061-T6 Aluminum and supports the camera-lens combination on the aft racks in the UHPV. The bracket is 0.7" tall, 5.1" long, 0.2" thick, and 0.1" thick on the sides. The UI-5140CP camera mounts from four M2.5 clearance screw holes on the symmetric center of the bracket and the two #4 counter-bore holes on the two ends of the bridge-shape mount onto the two #4-40 tapped holes on the side of the aft racks. With the placement of the camera-lens and bracket combination, it allows for both the external forward camera enclosure and the internal forward camera-lens combination to be operating from the same vertical plane. Since there are only two M2.5 clearance holes on each bracket, two brackets are used to mount the camera-lens combination to the electronic rack of the AUV.

4.3 Aurora External Downward Camera External Enclosure

4.3.1 Hull

Figure 15: Aurora External Downward Enclosure Hull

The hull (Figure 16) is made of 6061-T6 Aluminum and is similar in design to previous forward camera hull designs. The enclosure's length is 2.7" giving about 1.3" of space for the wires and the rest for the camera-lens combination. With the addition of the endcap hull (4.3.2), the overall length is shorter than previous designs and eases machinability of the part. The enclosure's inner diameter is 2.0", which is shorter than the previous designs because the bulkhead encompasses the lens and not the camera. The thickness of the hull's cylindrical base is 0.1", making the outer diameter of the cylinder 2.2". As a result of the smaller inner diameter, the outer diameter of the front and back faces is 3.0". There are three size 139 O-ring grooves with a 0.125" inset for viewport, flange, and endcap hull. In addition, eight #4-40 tapped holes are on both the front and back faces of the hull for the face seal to the flange and endcap hull, respectively. Most notably, eight #4-40 socket head cap screws on the back of the hull screw into the endcap hull from the hull side.

4.3.2 Endcap Hull

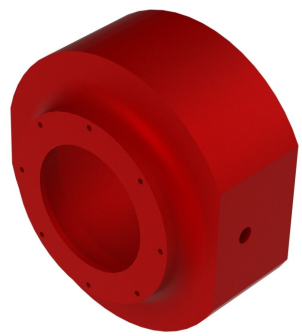
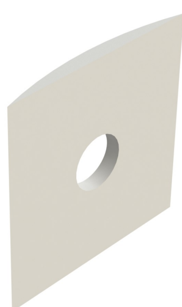
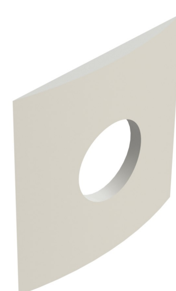


Figure 16: Aurora External Downward Enclosure Endcap Hull



(a) 5/16"-18 Fixer

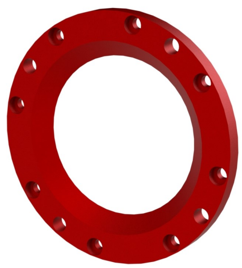


(b) 7/16"-20 Fixer

Figure 17: Aurora External Forward Camera Enclosure Fixers

The endcap hull (Figure 17) is made out of 6061-T6 Aluminum and is a new design implemented to give the electrical subteam additional space to manage and arrange the wiring for the SEACON connectors. By increasing the outer maximum diameter to 4.4", it allows a larger rotating bend for the wires without having to increase the overall length of the downward enclosure. Eight #4-40 tapped holes are spaced in a circular pattern on the front face of the endcap hull and align with the pattern of the holes on the back face of the hull to ensure that the enclosure is watertight. In addition, there are fousr #4-40 tapped holes spaced in a different circular pattern on the back face of the endcap hull for the bore seal to the endcap. Given the cylindrical shape of the endcap hull, cutouts on the sides create a flat surface for the two SEACON connectors: an MCBH-8 and a HUMG-2 that are face-sealed and screwed with 5/16" and 7/16" washers and 5/16"-20 and 7/16"-24 nuts. On the inside of the endcap hull, fixers (Figure 17 (a) and (b)) are used to replicate the outer flat surface, allowing for a flush surface and thus a tighter SEACON connector attachment.

4.3.3 Flange and Endcap



(a) Flange

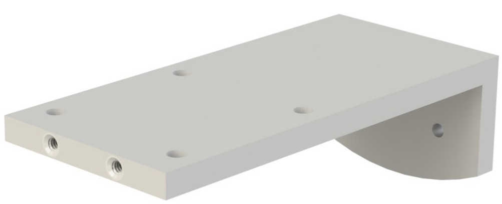
(b) Endcap

Figure 18: Aurora External Forward Camera Enclosure Flange and Endcap

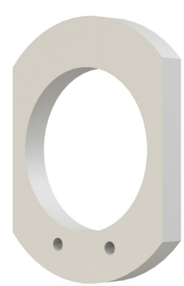
The flange (Figure 18 (a)) is made out of 6061-T6 Aluminum and is similar in dimension and feature to the flange of the external forward camera enclosure (refer to 4.1.2 Flange). A notable change, however, is that there are four #4-40 tapped holes for the attachment of the color perception palette using a male-female #4-40 threaded standoff.

The endcap (Figure 18 (b)) is made out of 6061-T6 Aluminum. The endcap will be directly bore sealed to the endcap hull and will have a diameter of 3.0", which is consistent with that of the hull. Four #4-40 threaded holes are spaced in a circular pattern on the back face of the endcap and align with the pattern of the holes on the back face of the endcap hull to ensure that the enclosure is watertight. In addition, there are two #4-40 threaded holes with a depth of 0.15" that allow for the attachment of the bracket assembly. Its overall thickness is 0.3" and uses a size 152 O-ring for the bore seal onto the endcap hull.

4.3.4 Bracket and Bulkhead



(a) Bracket



(b) Bulkhead

Figure 19: Aurora External Downward Camera Enclosure Bracket and Bulkhead

The bracket (Figure 19 (a)) is an L-shaped cantilever and is 3D-printed using ABS plastic that supports the camera-lens combination on the aft racks in the UHPV. The bracket is 0.875" tall, 2.8" long, and 0.15" thick. The UI-5250CP camera mounts from four #3 clearance screw holes on the symmetric center of the bracket and the two #4 counter-bore holes on the two ends of the bridge-shape mount onto the two #4-40 tapped holes on the side of the aft racks. Since there are only two #3 clearance holes on each bracket, there are two brackets used to mount the camera-lens to the AUV.

The bulkhead (Figure 19 (b)) is a 3D-printed support mechanism using ABS plastic to ensure that the camera, lens, and bracket remain stable whenever the AUV is in motion or operating the cameras and is similar in feature to the flange of the external forward camera enclosure (refer to 4.1.3 Bulkhead) except for the inner diameter as result of a different lens.

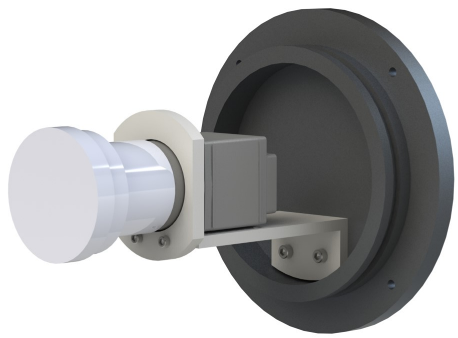


Figure 20: Aurora External Downward Enclosure Bracket Assembly

4.3.5 Viewport

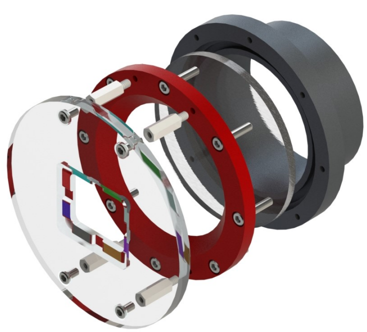
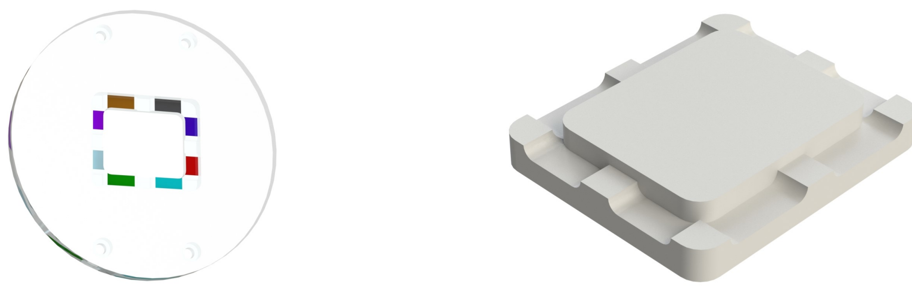


Figure 21: Aurora External Downward Enclosure Sectioned Viewport

The viewport contains both a 0.125" x 2.5" diameter disk of borosilicate glass disk and a 3.0" diameter clear epoxy disk (4.3.6 Color Perception Palette). The borosilicate glass disk is secured between the flange and the front face of the cylindrical hull of the UHPV and the clear epoxy disk is secured to the flange by a male-female threaded standoff. Two size 139 O-rings are on both sides of the borosilicate glass disk to ensure sealing of the enclosure (Figure 21).

4.3.6 Color Perception Palette



(a) Color Palette

(b) Mold

Figure 22: Aurora External Downward Enclosure Color Perception Palette

The color perception palette (Figure 22 (a)) is a newly implemented feature and utilizes a 3D-printed ABS plastic mold (Figure 22 (b)) to allow clear epoxy resin to form the shape desired for the palette. Most notably, the center rectangle forms an outer ring of eight colors in the downward camera's viewcone. In particular, the colors of known RGB values are manually chosen to best fit the ability to translate the underwater colors to surfaced colors. Using non-corrosive stickers and rectangular insets for sticker peeling in an alternating pattern, it allows for different colored stickers to be easily changed. And with the help of four #4 counter-bored holes and male-female #4-40 to #4-40 threaded standoffs, the palette is able to mount to the flange of the enclosure.

5 Current Status

The camera enclosures for Aurora are through the design process, but have yet to go through the manufacturing, sanding, anodizing, or integrating processes. Once these have been done (Fall 2021), the enclosures will be leaked tested to ensure the constraints and some of the objectives have been met. As more of these parts are tested, modifications will occur especially for the newly implemented designs and features.

6 Future Improvements

The decision to enlarge the endcap hull and add another endcap with a bore-seal turned out to be quite inefficient: greatly increasing the time and difficulty of machining the downward camera enclosure. In fact, this was only intended to ease the management of wires while minimizing the length of the enclosure. At the same time, the diameter of both forward and downward enclosure's hulls drastically decreased, but it simultaneously caused a visible and contrasting difference between the downward camera enclosure's hull and endcap. In the future, if I could redesign the downward camera enclosure, I would primarily want to implement a part that could redefine how wires bend and use space behind the camera, which would allow the electrical subteam to easily manage the connectors and also reach the objective of minimizing the length and the space used to enclose and seal the camera-lens combination. If even half of the wires behind the camera could be organized and have a direct line of path to where it needs to be connected, the length and space occupied by the enclosure could be reduced even further. Furthermore, if I could redesign the color palette, I would add more color slots. Another cool idea for this feature would be to have the color palette removable and attachable by command of the AUV.

Despite attempting to add a gimbal system to Aurora' cameras and finding that its utility doesn't outweigh the complexity it adds. However, I still feel as if adding this feature would advance toward the future of AUVs: opening up many new possibilities of underwater vision.

Appendices

A Purchased Components

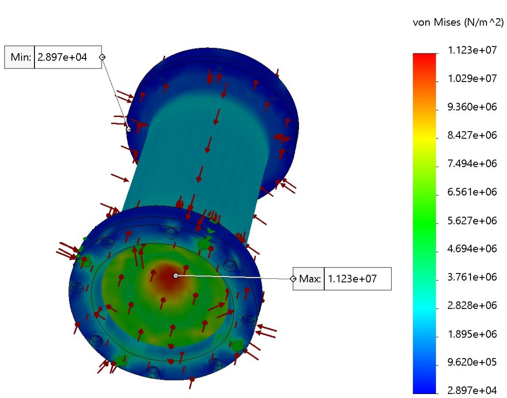
Component	Qty.
UI-5140CP Camera	2
NMV-4WA Lens	2
UI-5250CP Camera	1
Kowa LM3NCM Lens	1
2-1/2” x 1/8” Borosilicate Glass Disk	3
2-56 Thread Size, 0.100” Length Brass Heat-Set Inserts	4
Male-Female Threaded Hex Standoff 4-40 to 4-40 Thread	4

B Finite Element Analysis

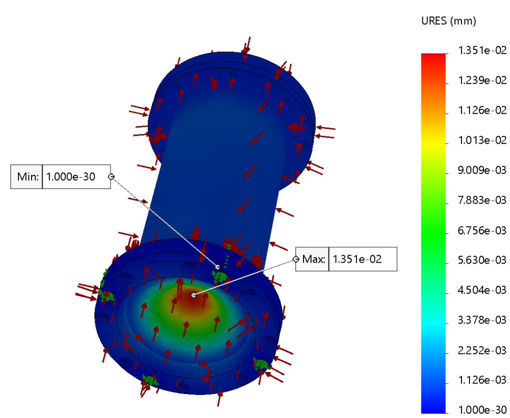
B.1 Forward External Camera Enclosure Assembly

Max Stress	1628.77 psi
Factor of Safety	18
Max Deformation	0.00053 in

Table 1: Forward External Camera Enclosure Assembly Simulation Data



(a) Equivalent Von-Mises Stress



(b) Total Deformation

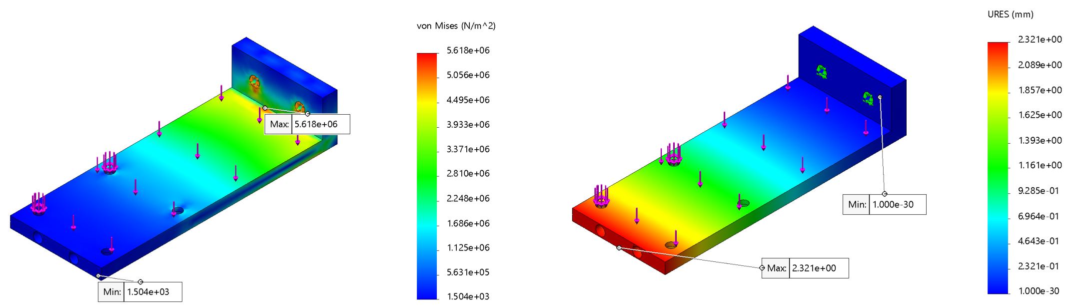
Figure 1: Forward External Camera Enclosure Assembly Simulation Results

The Aurora external forward camera enclosure was tested using SOLIDWORKS Simulation for equivalent von-Mises Stress at the pressure equivalent to that of 100 feet underwater, which is approximately 44.2076 psi. The safety factor is 18 when comparing the maximum stress found in the analysis, 1628.77 psi (1.12e+07 pa), to the yield strength of 6061-T6 Aluminum 35,000 psi. The total deformation under these pressure effects was 0.00053 inches (1.35e-02 mm).

B.1.1 Forward External Camera Bracket

Max Stress	815.11 psi
Factor of Safety	6.2
Max Deformation	0.091 in

Table 2: Forward External Bracket Simulation Data



(a) Equivalent Von-Mises Stress

(b) Total Deformation

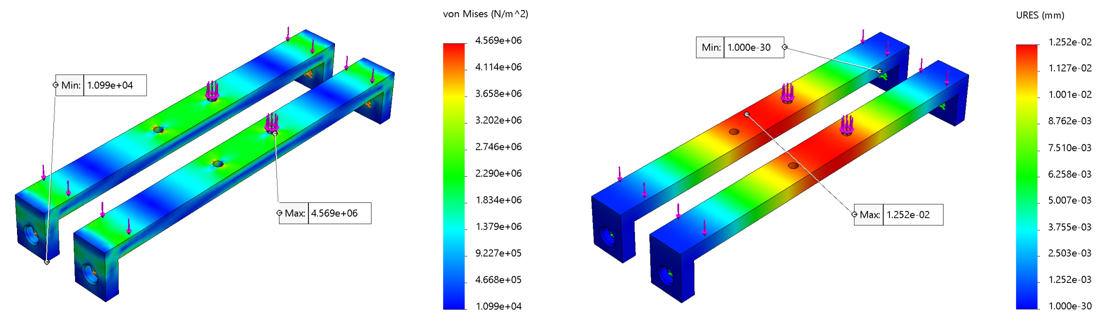
Figure 2: Forward External Camera Bracket Simulation Results

In the simulation, 10 N of force was applied to the end of the bracket, a magnitude that is approximately the force of the camera and lens combination done by gravity. The maximum stress of this application was 815.11 psi (5.62e+06 pa), which yields a factor of safety of 6.2. The maximum deformation of the 10 N force is 0.091 inches (2.31 mm).

B.2 Forward Internal Camera-Lens Combination Bracket

Max Stress	662.82 psi
Factor of Safety	60
Max Deformation	0.00049 in

Table 3: Forward Internal Camera-Lens Combination Bracket Simulation Data



(a) Equivalent Von-Mises Stress (b) Total Deformation

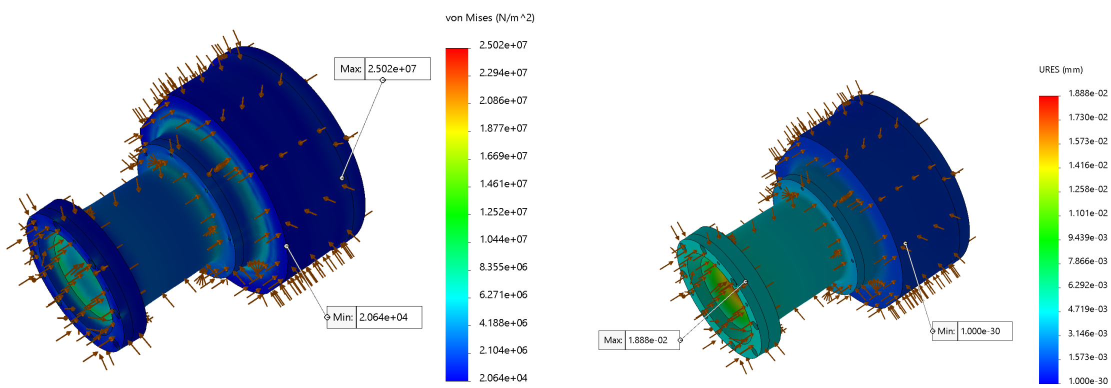
Figure 3: Forward Internal Camera-Lens Combination Bracket Simulation Results

In the simulation, a total of 40 N of force was applied to the top surfaces of the bridge-shaped brackets, a magnitude that is approximately twice the force of the camera and lens combination done by gravity. The maximum stress of this application was 662.82 psi (4.57e+06 pa), which yields a factor of safety of 60. The maximum deformation of the 40 N force is 0.00049 inches (1.25e-02 mm).

B.3 Downward External Camera Enclosure Assembly

Max Stress	3625.94 psi
Factor of Safety	8.2
Max Deformation	0.00074 in

Table 4: Downward External Camera Enclosure Assembly Simulation Data



(a) Equivalent Von-Mises Stress (b) Total Deformation

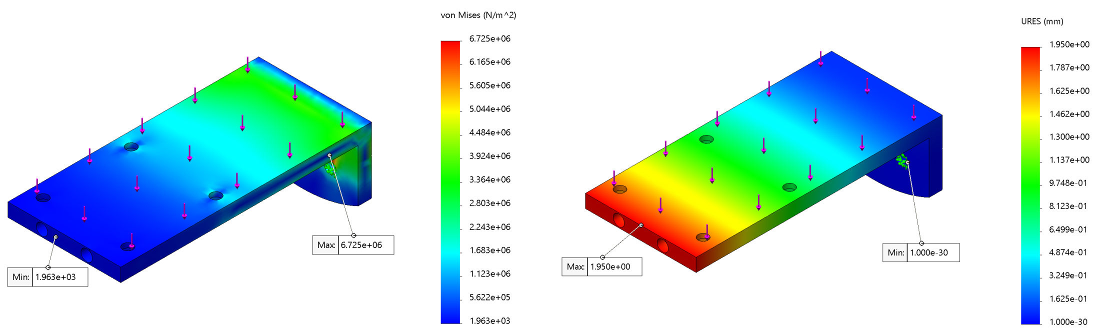
Figure 4: Downward External Camera Enclosure Assembly Simulation Results

The Aurora external downward camera enclosure was tested using SOLIDWORKS Simulation for equivalent von-Mises Stress at the pressure equivalent to that of 100 feet underwater, which is approximately 44.2076 psi. The safety factor is 8.2 when comparing the maximum stress found in the analysis, 3625.94 psi (2.50e+07 pa), to the yield strength of 6061-T6 Aluminum 35,000 psi. The total deformation under these pressure effects was 0.00074 inches (1.89e-02 mm).

B.3.1 Downward Camera Enclosure Bracket

Max Stress	976.10 psi
Factor of Safety	5.2
Max Deformation	0.077 in

Table 5: Downward Camera Enclosure Bracket Simulation Data



(a) Equivalent Von-Mises Stress

(b) Total Deformation

Figure 5: Downward Camera Enclosure Bracket Simulation Results

In the simulation, 10 N of force was applied to the end of the bracket, a magnitude that is approximately the force of the camera and lens combination done by gravity. The maximum stress of this application was 976.10 psi (6.73e+06 pa), which yields a factor of safety of 5.2. The maximum deformation of the 10 N force is 0.077 inches (1.95 mm).