Appendix D: Propulsion

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I. INTRODUCTION

Following the 2016 RobotX Competition, Minion's propulsion system was re-evaluated, finding three key weaknesses. First, the RDP (rim-driven propeller) thrusters were nearing their end of life. Second, Minion's maneuverability was inadequate. Third, deploying and retrieving Minion required team members to manually raise or lower the RDP thrusters. The propulsion system was redesigned to address these weaknesses.

The overall layout of the new propulsion system is similar to the old propulsion system. There are two "motor pods," one at the aft of each pontoon. The layout of each pod is shown in Fig 1. Each motor pod has one azimuthing Copenhagen Subsea VM RDP Thruster. This thruster is the newest iteration of the Torque-Jet thrusters on the previous system. Azimuthing is accomplished with Volz DA-30 Servos. These servos produce enough torque at high rotational speeds and are IP67 rated with additional testing for saltwater spray. Beaching is accomplished with a Linak LA-36 linear actuator, a component the team has prior experience with in hydrophone deployment.

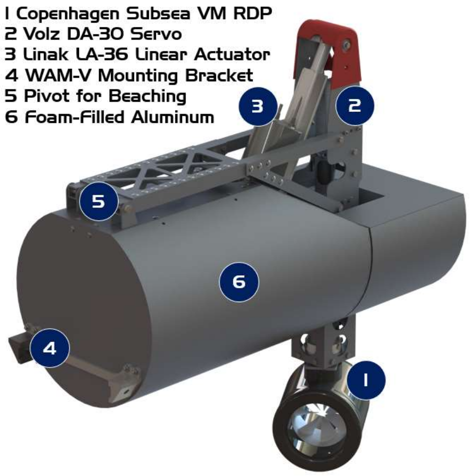

Fig 1. Azimuth and Beaching Enabled Propulsion System

II. REQUIREMENTS

Requirements for the updated propulsion system were based on the strengths and weaknesses of the 2014-2016 propulsion system. The requirements and justifications are as follows.

1) The system shall attach to the WAM-V boat using the attachment points detailed in the "RobotX Guide WAM-V Propulsion Examples" paper's section on "Other Alternatives." [1]

Since the WAM-V does not include a propulsion system, there is a pivot at the aft of each pontoon. These pivots serve as the mounting point for custom propulsion systems and allow these systems to pitch relative to the WAM-V pontoons. This pitching motion helps to ensure that the propulsion motor remains submerged. The motion is illustrated in Fig 2.

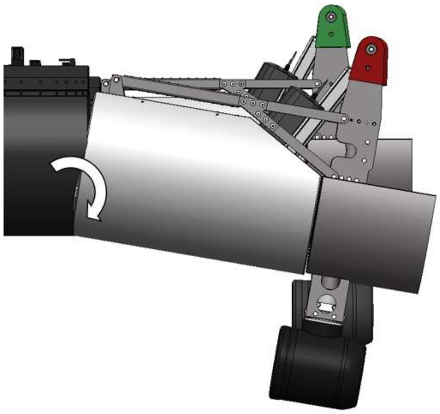

Fig 2. Propulsion Pitch Relative to WAM-V

2) The system shall be positively buoyant.

Requirements 1 and 2 together ensure that Minion fulfills the 2018 Maritime RobotX Challenge Rule 3.1.2. [2] The WAM-V requires additional buoyancy aft of the pontoon, or it risks capsizing.

3) The system shall be compatible with the Torque-Jet RDP thrusters, as well as suitable replacement thrusters.

As mentioned in the introduction to this appendix, the Torque-Jet RDP thrusters were to be replaced. However, the team wished to ensure that the propulsion system could run if there were delays in acquiring the new thrusters, or if one or both new thrusters were to be damaged.

4) The system shall be able to deploy the topmost point of the thrusters to a minimum depth of 4 inches below the bottom of the WAM-V pontoons.

This depth requirement helps to ensure that the thrusters always remain submerged.

5) The system shall be able to deploy the centerline of the thrusters to a minimum of 24 inches aft of the mounting points.

The intent of Requirement 5 is to ensure a sufficient moment arm from the thruster to Minion's CG. This moment arm is key to yaw acceleration.

6) The length of Minion including the system shall not exceed 16 feet.

Florida maritime law requires that vessels larger than 16 feet require a floatation device for each person on board, plus an additional floatation device [3]. This would require that Minion always have a personal floatation device despite being unmanned. To avoid complications with this regulation, 16 feet was accepted as Minion's maximum length.

7) The system shall be able to pan the thrusters +/- 85 degrees from parallel with the WAM-V pontoons.

170 total degrees of rotation with thrusters that can turn in forward or reverse means that thrust can be applied in nearly any direction from a top looking down view. While a range of motion of +/- 90 degrees would be more advantageous, limiting this requirement to 85 degrees improves the availability of off the shelf actuators that meet the required specifications.

8) The system shall be able to retract the thrusters from the water such that the bottommost point of the thruster is above the bottom of the WAM-V pontoons.

Requirement 8 protects the thrusters when trailering Minion or landing Minion on a beach. This prevents the thrusters from striking the ground or the trailer in these scenarios.

9) The system shall be compatible with 20-60V systems.

Requirement 9 ensures that Minion may continue to operate at either 25V or 50V nominal.

10) The system shall be able to operate continuously in the marine environment.

The marine environment is especially harsh on mechanical systems. Actuators need to be waterproof, and all materials need to be exceptionally corrosion resistant.

III. UPDATED THRUSTERS

For 2018, team Minion elected to continue with RDP thrusters. RDP thrusters have numerous advantages over electric trolling motors. First, the removal of a central shaft improves efficiency and reduces the likelihood of tangling with seaweed, anchor lines, and other debris. RDP thrusters are also inherently covered in a shroud and typically produce little noise. This minimizes their potential impact on marine wildlife, which is particularly important to the team since dolphins and/or manatees occasionally approach the ASV.

The dated Torque-Jet thrusters Minion used in 2016 were replaced with Copenhagen Subsea VM asymmetric thrusters. These thrusters are based on a similar design but are thoroughly updated. Improvements include inlet and outlet shrouds, revised propeller profiles, and revised internals. Due to these improvements, the Copenhagen Subsea thrusters offer improved efficiency, durability, and thrust capability compared to the Torque-Jets.

IV. BEARING MATERIAL SELECTION

Since all bearings in the propulsion system need to function both in and out of a saltwater environment, all bearing surfaces are static bushings. Bearings with moving pieces are susceptible to salt buildup over time, and underwater bearings do not function well out of water.

Multiple bushing materials were selected, and specific bushings were chosen from these selected materials based on the availability and cost of each.

The selected materials are Igus Iglide T-500, Iglide H-370, and Iglide J. Their applicable properties are shown in Table 1.

TABLE 1

IGUS BUSHING MATERIAL PROPERTIES [4] [5] [6]

Specification	Iglide T-500	Iglide H-370	Iglide J
Water Absorption (% Weight)	0.5	< 0.1	1.3%
Permissible Static Surface Pressure (psi)	21,760	10,880	5,075
Effective Coefficient of Friction	0.09 - 0.27	0.07 - 0.17	0.06 – 0.18

V. AZIMUTHING

I. *Geometry*

As specified in the requirements, the thruster must sit 4 inches below the nominal waterline. However, there are few high torque electric motors that are made to be used continuously underwater. Therefore, the azimuthing actuator must sit above water and some drive system must connect the azimuthing actuator to the thruster. To maximize efficiency, a direct drive was chosen. An exploded view of the drive shaft is shown in Fig 3.

Furthermore, the thruster must be retractable from the water for beaching. To simplify the direct drive system, the thruster and azimuthing assembly function as a single piece that can be raised and lowered for beaching.

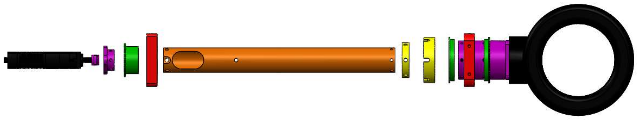

Fig 3. Azimuth Direct Drive Exploded View

To route the thruster cable, the direct drive is achieved with a hollow drive shaft. Adapters at the top and bottom of the shaft couple the actuator to the thruster. The drive shaft is supported by bearings at the top and bottom of the shaft to minimize radial force on the actuator. A section view of the top and bottom azimuth bearing assemblies is shown in Fig 4.

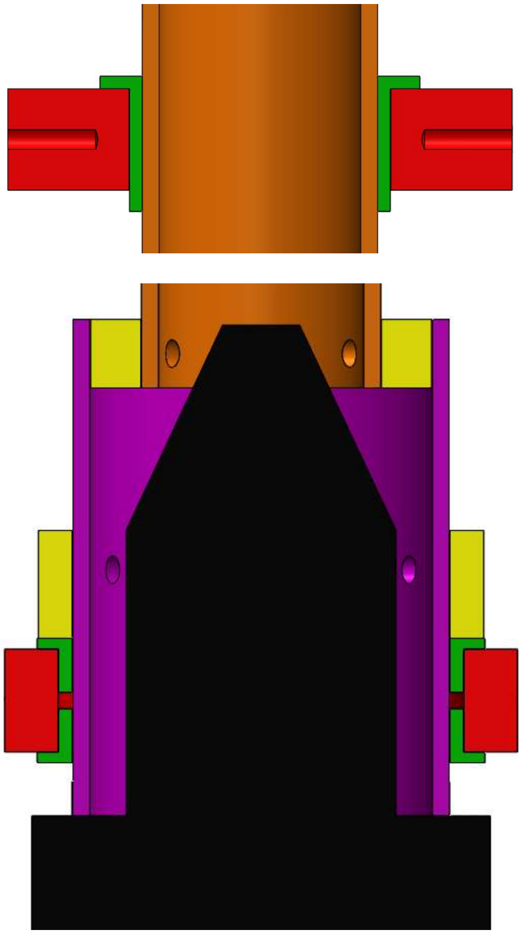

Fig 4. Azimuth Bearing Assemblies

The pieces shown in Fig 3 and Fig 4 are as follows:

- The orange tube is the hollow drive shaft.
- The black pieces are the thruster and azimuthing actuator.
- The green pieces are bushings.
- The red pieces support the bushings.
- The yellow pieces prevents the drive assembly from moving axially.
- The purple pieces couple the thruster and actuator to the driveshaft

II. *Structural Analysis*

To find the torque requirements for the actuator, the worst-case scenario must be considered. For azimuthing, that occurs when there is a maximum force of friction on the bushings. This maximum force of friction most likely results from the thruster's maximum load. To find the friction, the force reactions at the bearings during maximum thrust are found. These are multiplied by the bushing's static coefficient of friction and the radius of the shaft to be converted to the frictional torque opposing azimuthing. This frictional torque is what the azimuthing actuator must overcome. The torque was found using two methods to verify results: hand calculations modeling the system as a simply supported beam and an FEA model.

1) Method 1: Simply Supported Beam

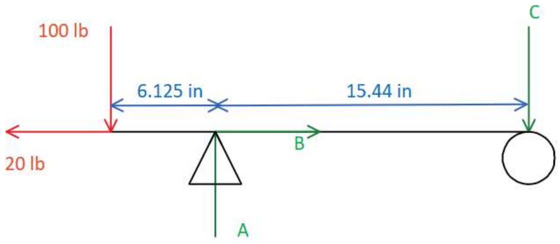

Fig 5. Azimuth Modeled as Simply Supported Beam

$$\Sigma F_x = 0$$
$$\mathrm{B} = 20\ \mathrm{lb}$$

$$\Sigma M = 0$$
$$(100)(6.125) = C(15.44)$$
$$\mathrm{C} = 39.7\ \mathrm{lb}$$

$$\Sigma F_y = 0$$
$$100 + 39.7 = A \rightarrow A = 139.7\ lb$$

$$\Sigma N = 20 + 39.7 + 139.7 = 199.4\ lb$$
$$F_f = \mu N = 0.1 * 199.4 = 19.94\ lb$$
$$\tau = Fr = 65.8\ lb * 1.1\ in = \mathbf{21.9\ in * lbf}$$

2) Method 2: FEA Reactions

For this FEA, a full thruster load of 100 lbf was applied to the azimuth tube model as shown in Fig 6. The red arrow indicates the force, which was applied at the distance of the motor centerline to the motor attachment plate. The 3 Igus bushings were constrained and monitored for their reaction forces.

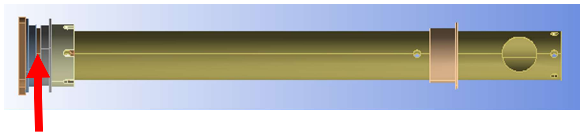

Fig 6. Azimuth FEA Load

This load case resulted in a net 180 lbf reacting from the bearing surfaces. With the 0.1 coefficient of friction mentioned above, a normal force of 18 lbf is present at the outer diameter of the bearings. To overcome this, the thruster must produce enough torque to overcome the normal force and the moment arm of the shaft radius (1.1 in). Therefore, the actuator must produce **19.8 in-lbf** of torque.

3) Evaluating the Methods

Since the methods have very close results, a nominal operating torque of 22 in-lbf was used.

III. *Actuator*

The selected actuator is the Volz DA-30 servo, shown in Fig 7. A summary of the applicable features of this actuator are in Table 2.

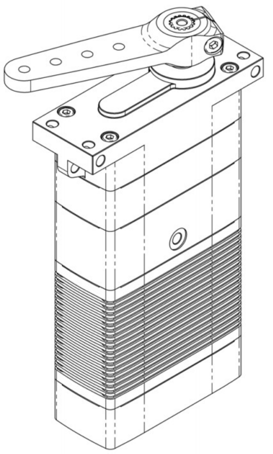

Fig 7. Volz DA 30 [7]

TABLE 2

VOLZ DA 30 APPLICABLE SPECIFICATIONS [7]

Specification	Value
Max Torque (continuous)	70.8 lbf-in
Max Torque (stall)	141.6 lbf-in
Supply Voltage Range	24 – 32 VDC
Max Travel Angle	±85° = 170° total travel
Environmental Rating	IP67
Salt Water Resistance	>100 hrs salt water spray

The environmental rating and supply voltage clearly meet the requirements, and the built-in position sensing, limited travel angle, and rated salt water resistance are massively advantageous features.

The Volz also meets the torque requirements, with a factor of safety of 3.2 for continuous operation and 6.4 if stalled. While this may appear excessive at a glance, there are many factors which could increase the resisting friction including drag, imperfect alignment, and the surface finish of the driveshaft.

VI. CHASSIS

I. *Design*

Construction of the propulsion system was largely driven by the methods easily available to our team. Embry-Riddle has CNC mills and lathes, but very limited capability in welding thin aluminum or bending sheet metal. Therefore, CNC machining was the primary method of manufacture for parts to minimize outsourcing and associated costs. Most parts are anodized 6061 or 5052 aluminum to prevent corrosion. Where higher strength material is required, 316 stainless steel is typically used. Parts are joined using aluminum rivets or 316 stainless steel bolts.

The main frame of the propulsion system is an assembly of gusseted 1 x 1 x .125'' square 6061 aluminum tube. This construction was chosen to allow easy mounting of the beaching and azimuth systems. It was also designed to allow any number of construction methods to the pod skin. The chassis is intended to take the greatest part of all loads, to minimize the stress on the skin assembly.

Fig 8. Primary Load Bearing Structure

II. *Structural Analysis*

1) Chassis

As stated, the motor pod chassis is designed to take the loads of the system, independent of the skin structure. FEA was run under two full thrust loading cases, assuming full thrust reverse and full thrust sideways. Gravity was also included, and buoyant forces were added where the pod skin meets the chassis. The model and loads are shown in
Fig 9.

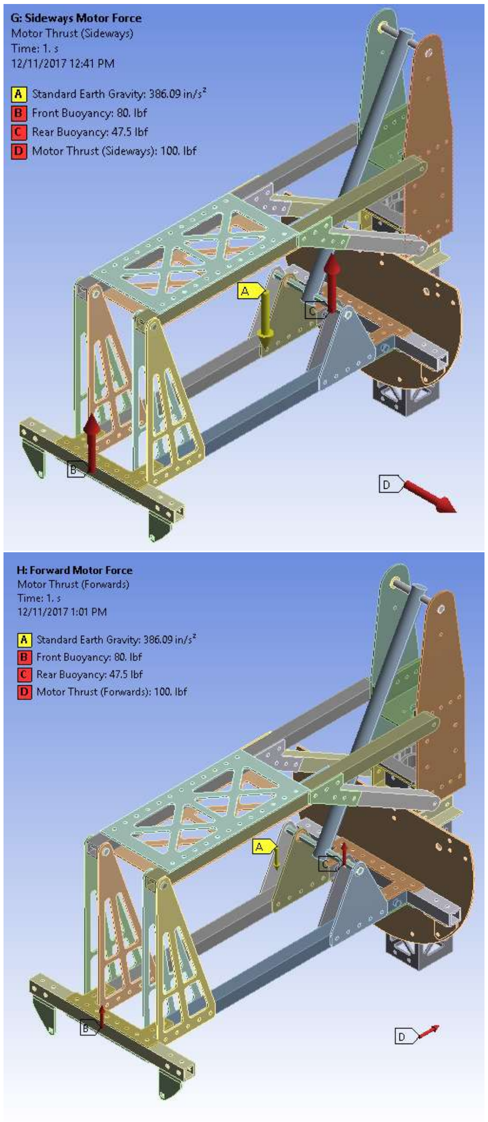

Fig 9. Model and Loads on Propulsion System Chassis

The sideways loading resulted in a max stress of about 25 ksi, in the bottom pin where the Linak attaches. These stresses are well under 316 Stainless Steel's yield strength of 34.8 ksi. [8] The 78.6 ksi stress is a false concentration at an interference where the azimuthing tubing meets the upper arm assembly. Results are shown in Fig 10 and Fig 11.

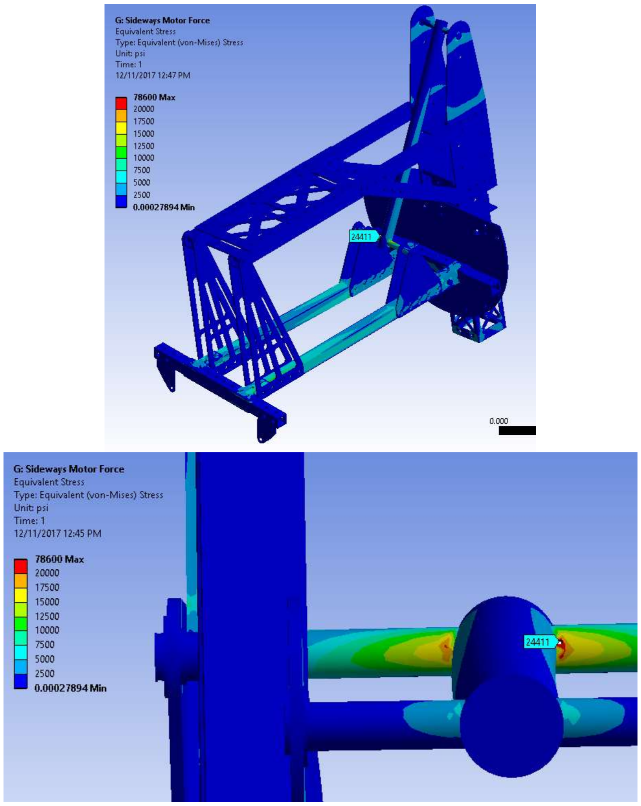

Fig 10. Full Sideways Thrust Chassis Stress

The full reverse thrust load case resulted in max stresses in the 15-20 ksi range where the Linak mounting plates meet the chassis. These stresses are well under 6061-T6's yield stress of 40 ksi. [9]

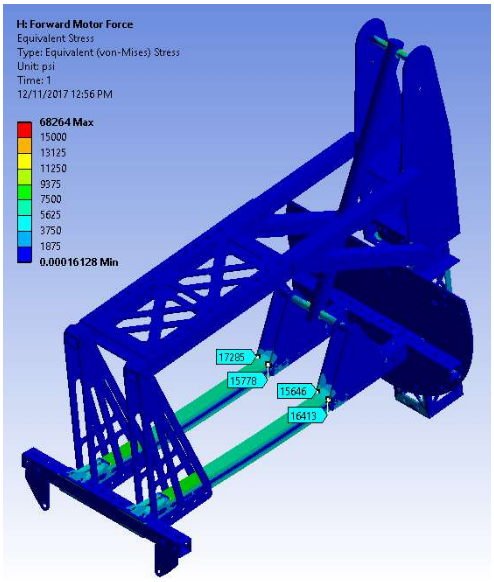

Fig 11. Full Reverse Thrust Chassis Stress

2) Azimuth Structure

The azimuthing portion of the system was independently evaluated under full forwards thrust and full reverse thrust to see the loading the Linak would experience.

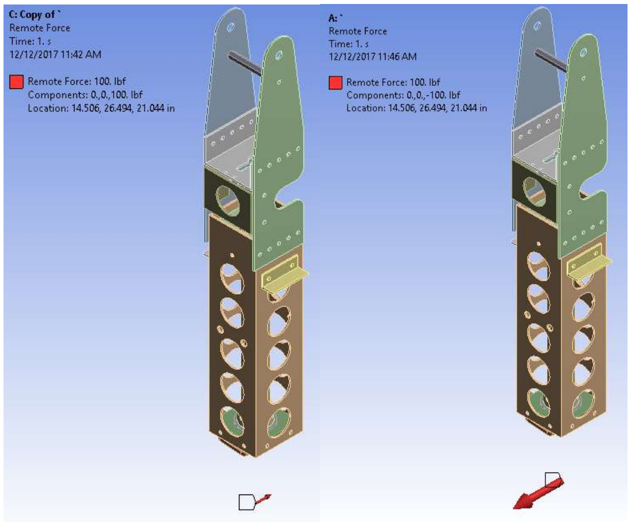

Fig 12. Full Forward Thrust (Left) and Full Reverse Thrust (Right)

Under full forward thrust, the Linak sees about 100 lbf, or 445 N of force. Under full reverse thrust, the Linak sees about 150 lbf, or 667 N. This is significantly less than the Linak's static holding force of 3400 N. This analysis also further proves the structural integrity of the azimuthing assembly as shown in Fig 13 and Fig 14.

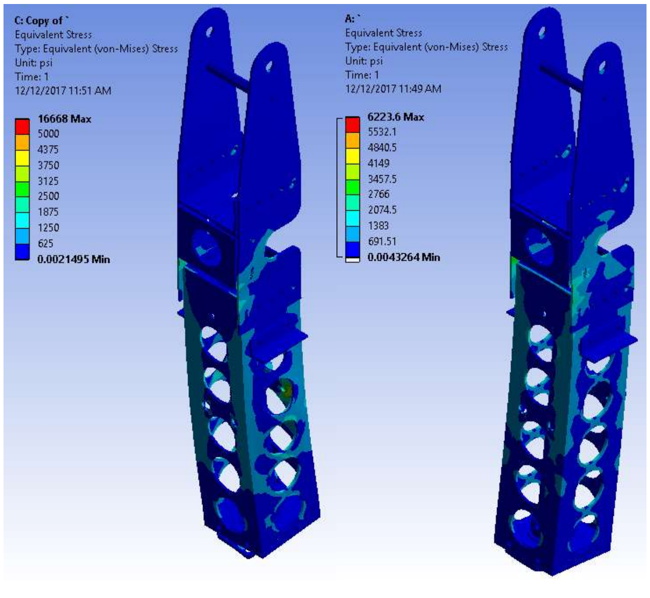

Fig 13. Forward Stresses (Left) and Reverse Stresses (Right)

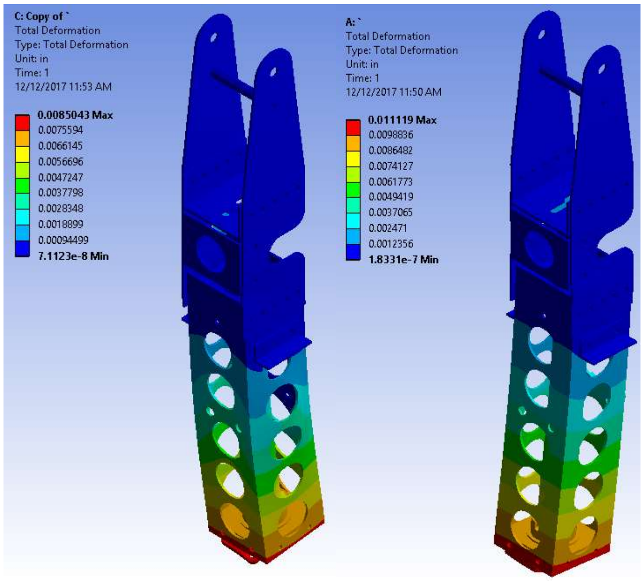

Fig 14. Forward Deflection (Left) and Reverse Deflection (Right)

VII. BEACHING

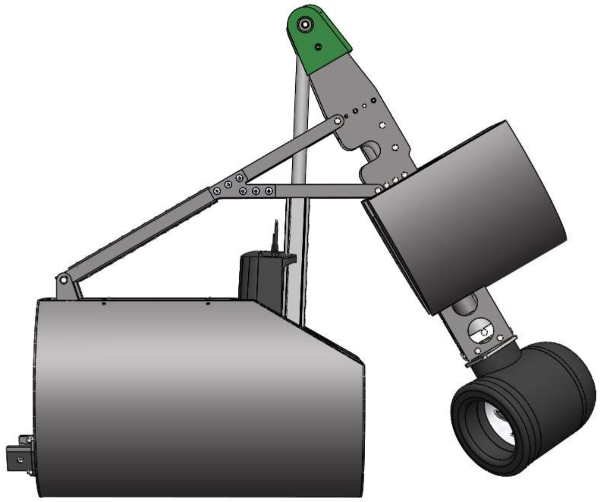

Fig 15. Motor Pod in Beached Configuration

The beaching motion is accomplished with a Linak LA-36 actuator. The Linak was selected due to an IP-66 dynamic and IP-69K static rating, and the team's experience using a smaller Linak in very close proximity to the water. The selected LA-36 also has 400mm of travel, end stop signals, a max actuation force of 2600N, and a static holding force of 3400N. [10] These forces are more than sufficient as proven in the azimuth structural analysis above.

I. *Skin*

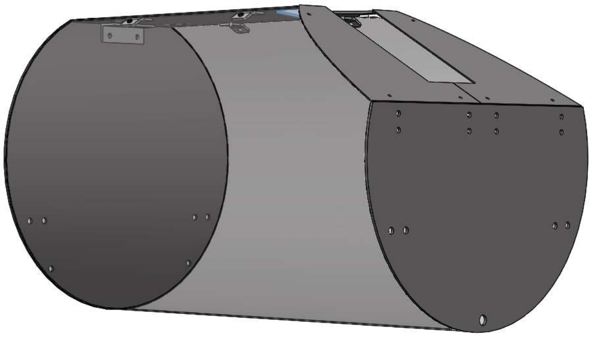

Fig 16. Skin

To contain the motor pod's buoyancy and give visual continuity from the WAM-V's pontoons, most of the motor pods are surrounded by a 16.25-inch diameter aluminum skin. Aluminum was chosen over fiberglass (which the previous propulsion system used) due to fiberglass's tendency to crack and shatter on impacts. This skin is epoxied to the main chassis using 3M EC2216 Scotch-Weld Epoxy. Other fastening methods such as brackets with rivets were not chosen due to increased likelihood of leaks through additional holes.

Buoyancy is accomplished using a closed cell expanding foam fill with Dow Froth-Pak. This ensures that in the case of any leaks, the pod will not fill with water.

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