MECHANICAL ENGINEERING DESIGN & SUBSEA ROBOTICS DOCUMENTATION

MATE ROV MODULAR CLAW ASSEMBLY

Design of a Modular Actuator Hub, Dual-Axis Rack-and-Pinion Transmission, and Zero-Pressure Medusa Encirclement End-Effector for Underwater Remotely Operated Vehicle

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CAD PLATFORM: SOLIDWORKS

ASSEMBLY SCALE: 30 Components

Executive Engineering Summary: This technical report documents the complete mechanical design, kinematic modeling, and design-for-manufacturing (DFM) evaluation of a waterproof, modular claw assembly engineered for the Marine Advanced Technology Education (MATE) Remotely Operated Vehicle (ROV) competition. Tasked with retrieving fragile deep-water *Medusa* jellyfish specimens without inflicting compressive tissue damage, the assembly replaces conventional pinch grippers with a synchronized, semi-cylindrical encirclement cage driven by a gasket-sealed, dual-axis rack-and-pinion gearbox and quick-release modular hub.

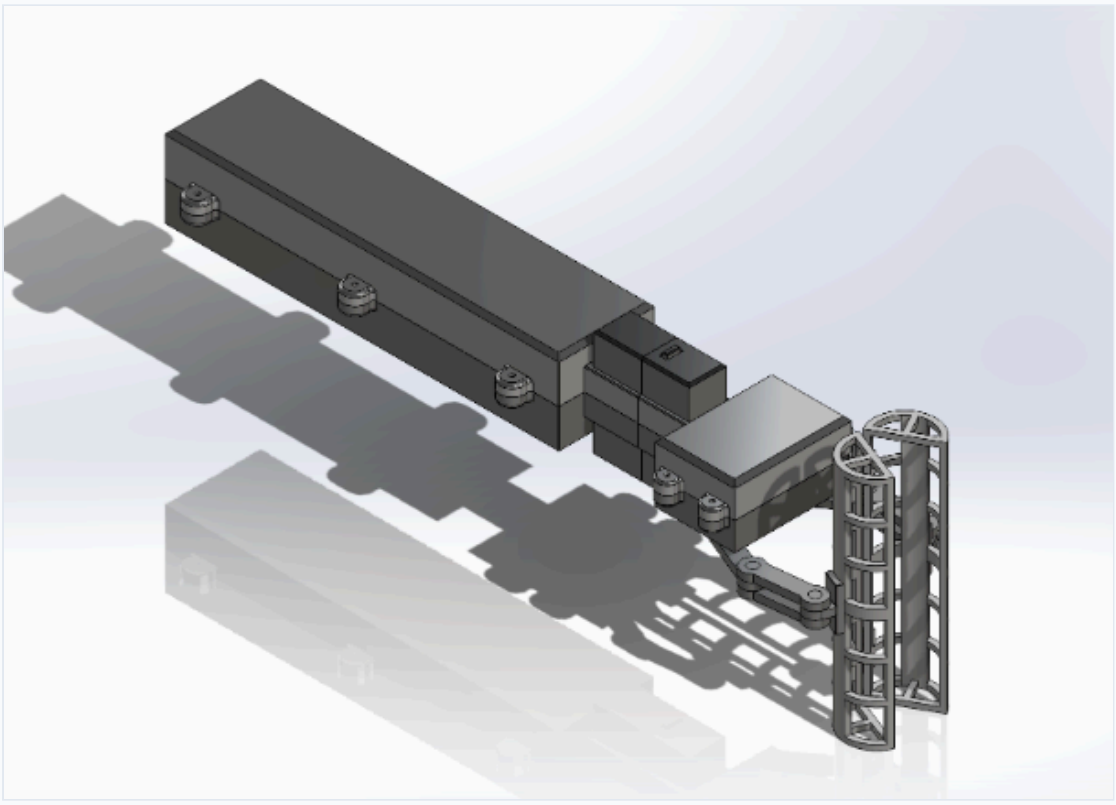


Figure 1: Full isometric SOLIDWORKS assembly rendering of the 30-component MATE ROV Modular Claw Assembly, illustrating the waterproof Servo Housing, dual quick-release snap-fit latches, Gearbox hub, four-bar rotary linkage arms, and semi-cylindrical ribbed encirclement cages.

1.0 Table of Contents & Architectural Overview

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1.1 Problem Definition & Operational Background

This engineering project originated within the robotics and engineering program in preparation for the Marine Advanced Technology Education (MATE) Remotely Operated Vehicle (ROV) competition (**MATE ROV Competition, 2025**). Among the underwater intervention tasks specified by the competition guidelines, one of the most mechanically demanding challenges involves the delicate capture, containment, and recovery of a benthic or pelagic *Medusa* (jellyfish) specimen submerged in the mission tank. Conventional robotic end-effectors rely on frictional pinch claws that secure targets by applying normal clamping force across opposing jaws. When applied to gelatinous marine organisms or soft-bodied competition props, compressive clamping causes structural deformation or specimen damage.

To eliminate compressive contact stress entirely, the core engineering objective was defined as the invention of an original, fully waterproof mechanical claw assembly that encloses the target *Medusa* within a protective geometric volume rather than squeezing it. Furthermore, because the attachment is intended as a specialized, competition-grade prototype fabricated via polymer additive manufacturing (3D printing) rather than a high-volume commercial product, design optimization prioritized functional reliability, submerged sealing integrity, compact ROV mounting envelope, and modular field serviceability over mass-production unit cost.

1.2 Proposed Mechanical Design & Conceptual Architecture

The proposed design addresses the zero-pressure capture requirement by replacing friction jaws with a pair of opposing, semi-cylindrical ribbed cages hinged along their rear vertical edge. When actuated, the two semi-cylindrical halves sweep through a synchronized arc to form a closed cylindrical containment chamber dimensioned around the *Medusa* specimen. Because the entire mechanism operates submerged atop or beneath the ROV frame, all electronic and primary drive elements—specifically the actuator servo motor and power battery—must be isolated from ambient water ingress inside gasket-sealed enclosures.

Prior to 3D parametric modeling in SOLIDWORKS and Autodesk Fusion 360, the mechanical layout was synthesized through freehand conceptual sketching (Figure 2). The conceptual workflow established a linear-to-rotary power transmission train: a stationary servo motor housed inside a rear waterproof chamber drives a pinion gear, which translates a central linear rack forward and backward through an O-ring/gasket-sealed neck into a detachable front gearbox. Inside the gearbox, orthogonal teeth on the rack mesh simultaneously with two counter-rotating spur gears coupled to rotary linkage arms, opening and closing the encirclement cage.

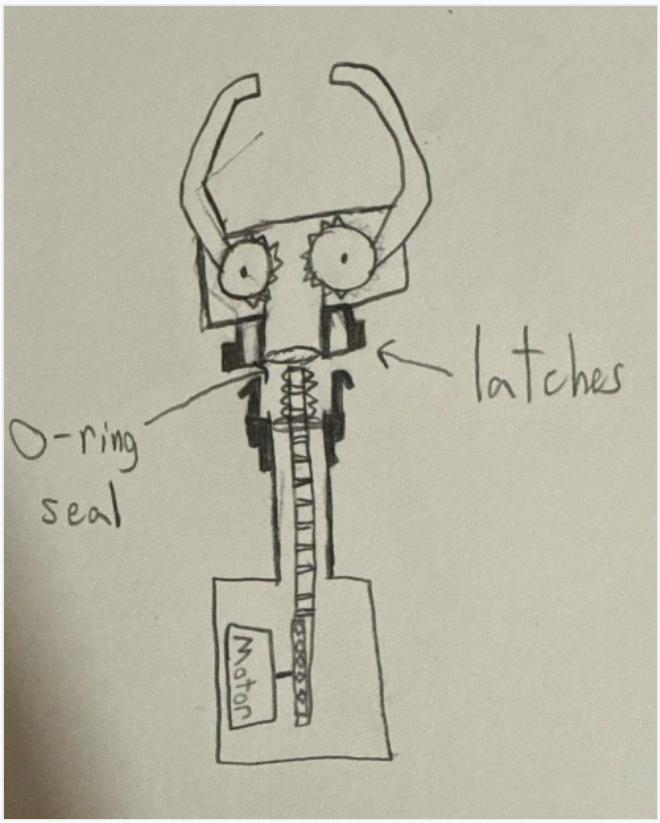


Figure 2: Original conceptual hand sketch of the MATE ROV claw architecture, establishing the waterproof rear motor housing, central linear rack transmission, O-ring neck seal, quick-disconnect housing latches, and dual counter-rotating spur gears driving the upper capture jaws.

1.3 Comprehensive List of Deliverables & 30-Component Bill of Materials

To transition the conceptual architecture into a fully verified virtual prototype, the engineering deliverables were organized across technical documentation, parametric part models, sub-assembly kinematic studies, and ANSI-standard multiview engineering drawings:

- **Engineering Report Documentation:** Formal problem definition, conceptual design synthesis, subsystem CAD methodology, additive manufacturing evaluation, and kinematic stability analysis.
- **Parametric CAD Part Models (SOLIDWORKS & Autodesk Fusion 360):** Individual `.SLDPRT` and `.F3D` part models covering all custom-designed structural housings, gears, linkages, cages, hinges, and snap-fit latches.
- **Assembly & Kinematic Models:** Full 30-component master assembly model with mechanical gear, rack-and-pinion, concentric, and width mates, accompanied by an exploded isometric assembly configuration.
- **Engineering Production Drawings:** Detailed multiview orthographic drawings with isometric projection, exploded view drawing with BOM item balloons, complete Bill of Materials table, and critical dimensional tolerances.

Item	Component / Part Name	Qty	Material / Type	Primary Subsystem Function
1	Bottom Servo Housing	1	PETG / ABS (3D Printed)	Lower waterproof enclosure & linear rack guide track
2	Top Servo Housing	1	PETG / ABS (3D Printed)	Upper waterproof enclosure cover with 6 screw tabs
3	Bottom Gearbox Housing	1	PETG / ABS (3D Printed)	Lower gear chamber with dual internal gear support bosses
4	Top Gearbox Housing	1	PETG / ABS (3D Printed)	Upper gear cover with dual rotary shaft through-bores
5	Dual-Axis Linear Rack	1	Nylon 12 / Delrin (POM)	Translates servo rotation into dual-gear counter-rotation
6	10 mm Drive Pinion Gear	1	Nylon 12 / Delrin (POM)	18-tooth spur gear coupled directly to servo output spline
7	6 mm Rotary Arm Spur Gear	2	Nylon 12 / Delrin (POM)	18-tooth gears meshing with lateral rack teeth in gearbox
8	Vertical Rotary Arm Shaft	2	PETG / Carbon-Reinforced	Vertical shaft passing through gearbox bore with square socket
9	Top 90° Horizontal Rotary Arm	2	PETG / Carbon-Reinforced	Forward-projecting crank arm with square drive key & pivot pin
10	Additional Linkage Arm (Elbow Bar)	6	PETG / ABS (3D Printed)	Symmetrical 3-layer double-shear elbow linkage bars (3 per side)
11	Semi-Cylindrical Caged Claw	2	PETG (Low-Density Fill)	Ribbed semi-cylindrical encirclement cage for *Medusa*
12	Cage Hinge Part 1 (Female Clevis)	2	PETG / ABS (3D Printed)	Upper and lower double-knuckle female rear cage hinges
13	Cage Hinge Part 2 (Male Pin Block)	2	PETG / ABS (3D Printed)	Upper and lower interlocking pin knuckles for rear cage seam
14	Latch Insertion Block (Latch 1)	2	Flexible Tough PLA / PETG	Cantilever snap-fit male latch mounted on top/bottom housing
15	Latch Reception Block (Latch 2)	2	PETG / ABS (3D Printed)	Female latch receptacle with integrated top release button

Item	Component / Part Name	Qty	Material / Type	Primary Subsystem Function
16	Perimeter Elastomeric Gasket Set	2	EPDM / Buna-N Rubber	Waterproof compression seals for Servo Housing & Gearbox

1.4 Project Development Schedule & Milestone Log

The modeling, refinement, and assembly verification of the MATE ROV Modular Claw Assembly were executed across a structured four-week engineering schedule between April 28, 2025, and May 21, 2025, progressing systematically from external waterproof housings to internal transmission gears, linkages, and final multiview production drawings.

Date	Engineering Task & CAD Modeling Activity	Specific Deliverables Completed
04/28/2025	Conceptualize the underwater capture problem and evaluate candidate mechanical solutions.	Brief technical proposal completed and raw conceptual sketches of the mechanism created.
04/29/2025	Model the semi-cylindrical containment cage dimensioned to house the *Medusa* specimen.	Finished parametric part file for the Caged Claw described in Section 2.4.
04/30/2025	Create the initial Top and Bottom Servo Housing enclosure models.	Initial housing geometry modeled; initiated technical documentation for Section 2.1.
05/03/2025	Rework the Servo Housing model to incorporate dedicated internal mounting walls for the servo and rack guide channel; model Top and Bottom Gearbox halves.	Updated Section 2.1.1 documentation and completed Section 2.1 housing specifications.
05/04/2025	Conceptualize the rack-and-pinion transmission system, initially testing the built-in SOLIDWORKS Toolbox gear generator.	Initiated Section 2.2 transmission documentation and gear ratio sizing.
05/05/2025	Replace the default SOLIDWORKS gear function with custom precision tooth sketches (lines and tangent arcs) and linear/circular patterns to streamline assembly mating.	Reworked pinion and dual-axis rack CAD part files for deterministic tooth engagement.
05/08/2025	Model the two-piece 90° rotary arms, the 6 mm arm spur gears, and the symmetrical hinged elbow linkage bars connecting the rotary arms to the cage.	Completed Section 2.2 and Section 2.3 (including Subsections 2.3.1, 2.3.2, and 2.3.3).
05/09/2025	Design the interlocking rear door-style hinges connecting the two semi-cylindrical cages together.	Completed hinge CAD part files and finalized Section 2.4 documentation.
05/12/2025	Initiate master SOLIDWORKS assembly: mate the linear rack inside the Servo Housing guide, pass vertical rotary arms through the Gearbox, lock the 6 mm gears to the arms, and mate Gearbox to Servo Housing.	Established primary sub-assembly kinematic constraints; initiated Section 2.6.

Date	Engineering Task & CAD Modeling Activity	Specific Deliverables Completed
05/13/2025	Identify requirement for a structural quick-release coupling to lock the Gearbox to the Servo Housing; initiate latch part modeling.	Started Section 2.5 documentation and cantilever snap-latch geometry.
05/14/2025	Continue master assembly: refine mechanical mates between gear teeth and rack planes, and mate rear hinges to the dual cages.	Verified full kinematic chain and audited all assembly mates for interference.
05/16/2025	Finalize part files for the Latch Insertion and Reception blocks and mate both sets onto the top and bottom housing seam.	Completed Section 2.5 and locked housing interface in master assembly.
05/19/2025	Generate exploded isometric assembly view and verify all 30 component instances.	All CAD part and assembly files finalized; Section 2.6 completed.
05/21/2025	Produce final multiview orthographic drawing package, BOM table, balloon callouts, and compile bibliography.	Engineering drawing PDF package and Section 4.0 References completed.

2.0 Detailed Mechanical Design & Subsystem Engineering

2.0.1 Initial Engineering Thought Process & Submerged Packaging

At the outset of the detail design phase, two non-negotiable physical parameters governed all geometric decisions: the complete claw assembly had to remain compact enough to mount cleanly within the ROV payload frame, and all electromechanical drive components had to be hermetically isolated for submerged operation. Consequently, the design methodology followed an outside-in structural hierarchy—establishing the waterproof Servo Housing and Gearbox shells first so that internal wall thicknesses, gasket sealing lands, fastener bosses, and shaft pass-through clearances could rigidly define the envelope for the internal rack-and-pinion drive mechanism.

2.1 Waterproof Housing Units

2.1.1 Servo & Battery Housing Assembly

The Servo Housing consists of two mating clamshell halves—the Bottom Servo Housing and Top Servo Housing—engineered to enclose and protect the waterproof servo actuator and onboard battery pack. To achieve uniform clamping pressure along the perimeter elastomeric rubber gasket, six semi-circular screw bosses (three along each longitudinal side) are integrated into the exterior walls. When bolted together, the opposing flanges compress the rubber gasket into a continuous perimeter seal.

Internally, the housing was modeled using a shelled boss-extrude workflow followed by thin internal rib extrusions that form a dedicated retention pocket for the servo body and a narrow forward linear guide channel. This forward channel constrains the linear rack to pure axial translation ($\pm X$ axis), preventing lateral deflection or gear tooth skipping under load.

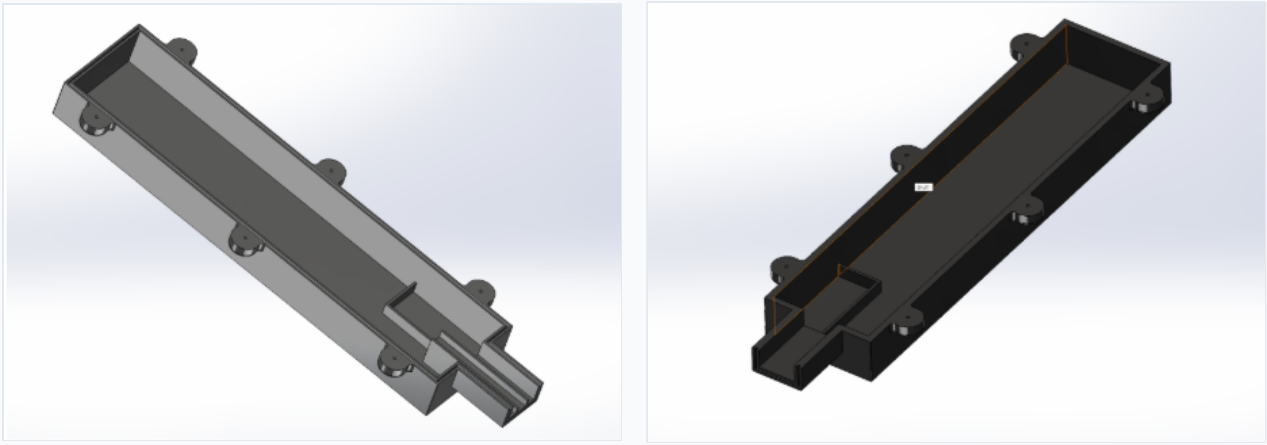


Figure 3: SOLIDWORKS part models of the **Bottom Servo Housing** (left) and **Top Servo Housing** (right). Six opposing screw bosses compress a perimeter rubber gasket, while internal walls align the servo motor and guide the linear rack.

2.1.2 Gearbox Enclosure Assembly

The Gearbox houses the two 6 mm rotary arm spur gears, the lower vertical shafts of the rotary arms, and the orthogonal front segment of the linear rack extending from the Servo Housing. Its waterproofing and fastening architecture mirrors that of the Servo Housing, utilizing four exterior screw bosses (two on each side) and a recessed perimeter gasket groove machined into the mating wall rim.

To support the rotational loads of the claw linkage, the Gearbox incorporates two critical cylindrical features: on the interior floor of the Bottom Gearbox, two circular sketches are boss-extruded upward to serve as bearing pedestals that locate the 6 mm gears vertically; on the Top Gearbox cover, two concentric circular sketches are cut-extruded completely through the upper face, allowing the vertical shafts of the rotary arms to emerge from the gearbox and connect to the external 90° linkage arms.

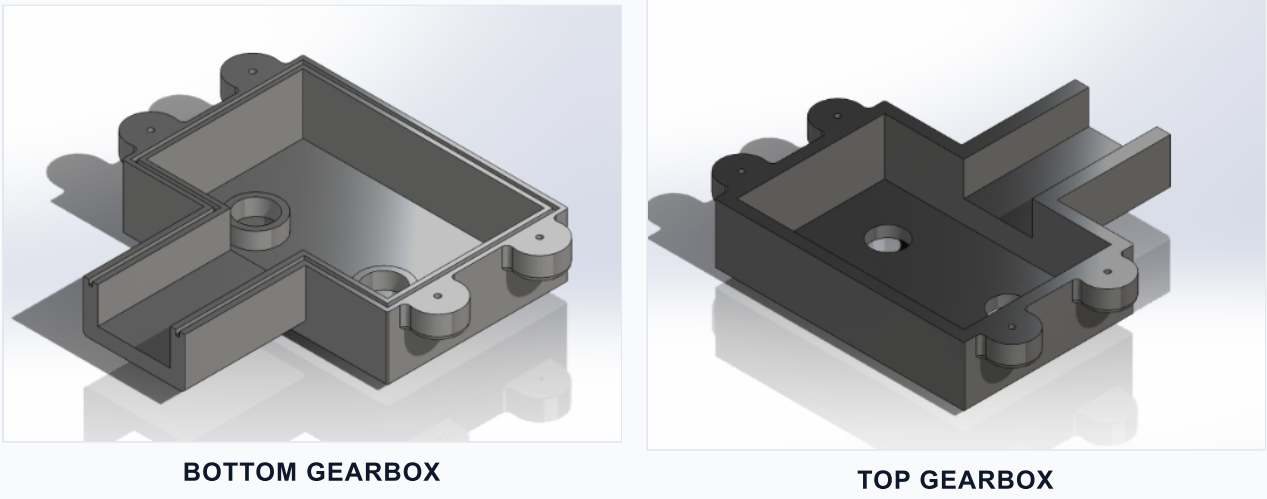


Figure 4: SOLIDWORKS part models of the **Bottom Gearbox** (left) and **Top Gearbox** (right), illustrating the floor boss extrusions that support the internal spur gears and the upper cut-extruded bores that guide the vertical rotary arm shafts.

2.2 Kinematic Transmission & Movement Operation

2.2.1 Dual-Axis Rack and Pinion Gears

The primary mechanical transmission enabling the claw to open and close is a dual-stage rack-and-pinion system. In the first stage, a stationary servo motor mounted inside the Servo Housing rotates a 10 mm wide spur gear (the drive pinion). Because the servo axis is fixed, rotation of the 10 mm pinion drives the linear rack forward or backward along the guide channel linking the Servo Housing and the Gearbox. In the second stage, the distal end of the linear rack enters the Gearbox, where a perpendicular double-sided tooth profile meshes simultaneously with two 6 mm wide spur gears fused to the left and right rotary arm shafts.

A significant CAD modeling challenge during this phase involved generating robust, mate-compatible gear teeth on both the circular gears and the linear rack. While SOLIDWORKS includes a standard Toolbox gear utility, its complex spline surfaces created mating instabilities during full-assembly kinematic solving. Consequently, the built-in gear function was replaced with a deterministic sketch-driven method: a single tooth profile was constructed using tangent lines and arcs, extruded to the required face width (10 mm for the servo pinion and 6 mm for the rotary arm gears), and replicated via a circular pattern for the gears and a linear pattern for the rack. On the forward portion of the rack that enters the Gearbox, the exact same linear tooth pattern was extruded on the perpendicular vertical planes so it drives both rotary arm gears in synchronized opposition.

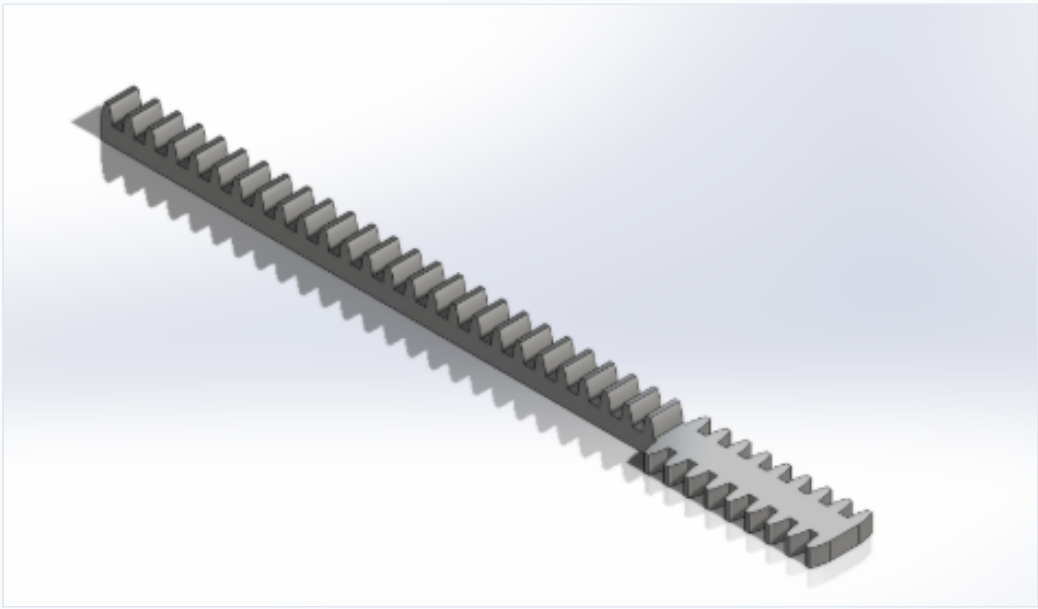


Figure 5: Isometric SOLIDWORKS model of the **Dual-Axis Linear Rack**, featuring a primary row of transverse teeth driven by the stationary servo pinion and a perpendicular dual-sided front tooth section that rotates both gearbox spur gears simultaneously.

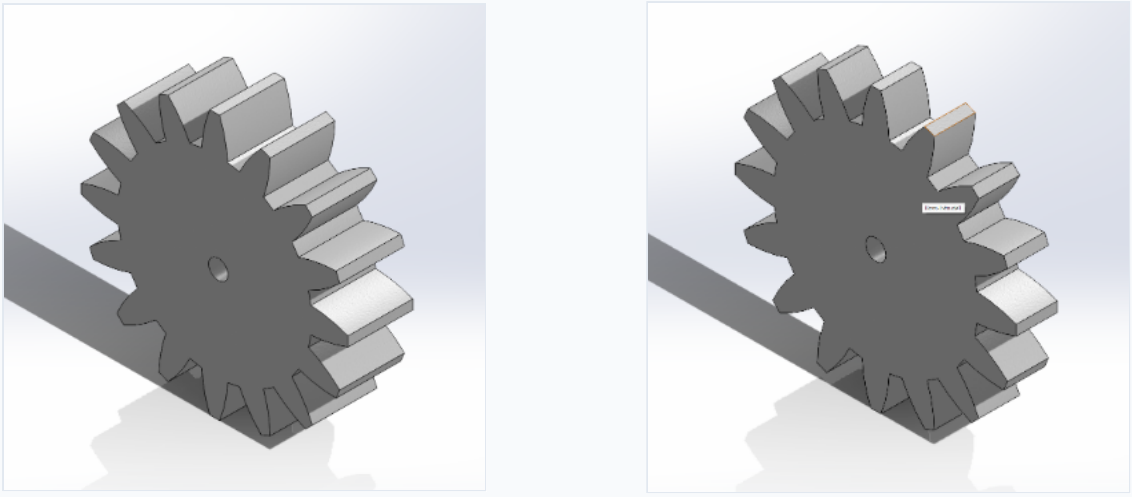


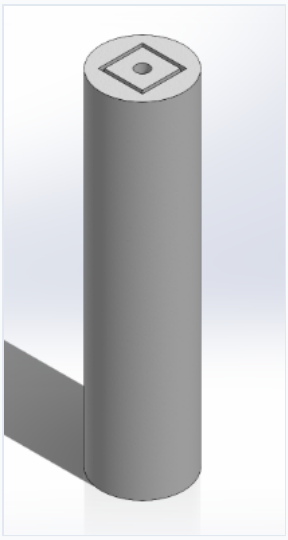
Figure 6: SOLIDWORKS part models of the **10 mm Drive Pinion Gear** (left) and the **6 mm Rotary Arm Spur Gear** (right). Both gears utilize an identical 18-tooth circular pattern to maintain uniform diametral pitch across the linear rack.

2.3 Rotary Actuation & Four-Bar Linkage Components

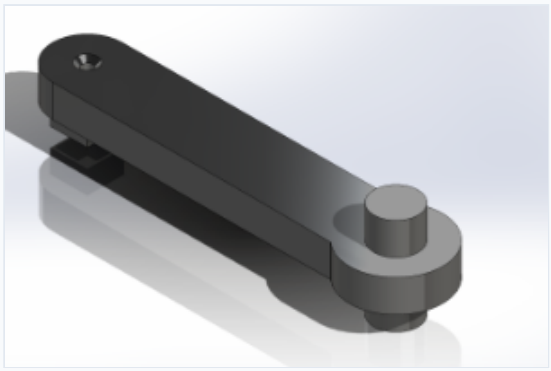
2.3.1 Two-Piece Modular Rotary Arms

The rotary arms directly transfer the torque of the internal 6 mm gearbox spur gears to the external cage linkages. In the assembled configuration, two vertical rotary shafts rest on the internal bearing pedestals of the Bottom Gearbox, pass through the circular bores of the Top Gearbox, and bend 90° forward to drive the elbow hinges.

During design-for-assembly (DFA) analysis, a critical physical constraint emerged: because the internal 6 mm spur gear is fused to the lower vertical shaft inside the Gearbox and has a larger outer diameter than the Top Gearbox pass-through bore, a monolithic 90° bent arm could never be inserted through the Top Gearbox cover during physical assembly. To solve this manufacturability constraint, the rotary arm was engineered as a detachable two-piece assembly (Figure 7): the **Vertical Rotary Arm** slides through the Gearbox bore first, and the **Top Rotary Arm** subsequently locks onto its top face via a recessed square torque-transfer socket and central fastener bore.



VERTICAL ROTARY ARM

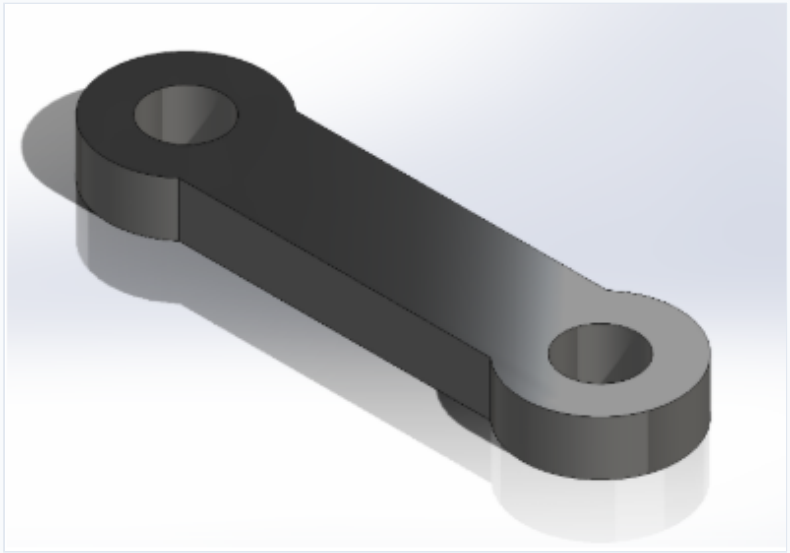


TOP ROTARY ARM

Figure 7: SOLIDWORKS part models of the two-piece modular rotary arm: the **Vertical Rotary Arm** (left) passes upward through the Gearbox cover, while the **Top Rotary Arm** (right) mates onto the recessed square socket to complete the 90° bend.

2.3.2 Symmetrical Elbow Hinges & Additional Linkage Arms

To convert the rotational arc of the Top Rotary Arms into smooth, symmetrical closure of the dual encirclement cages, a multi-layer hinged elbow joint was engineered on each side of the assembly. Each elbow joint is constructed in three vertical layers (a double-shear clevis arrangement): a single **Additional Arm** coupled to the Top Rotary Arm occupies the middle layer of the hinge pin, while two identical **Additional Arms** attached to the Caged Claw connect to the top and bottom layers of the elbow hinge. This symmetrical three-layer stack eliminates eccentric bending moments on the hinge pin and stabilizes the vertical cages against pitch deflection.



ADDITIONAL ARM

Figure 8: SOLIDWORKS part model of the symmetrical **Additional Arm** used in the three-layer elbow linkage between the 90° rotary arm and the semi-cylindrical cage mounts.

2.4 Medusa Encirclement Cage & Interlocking Hinges

The Caged Claw represents the primary mission-critical end-effector of the assembly. To ensure the fragile *Medusa* jellyfish is never subjected to crushing forces, each half of the claw is modeled as a hollow semi-cylindrical shell that closes around the perimeter of the specimen rather than gripping its bell tissue. Starting from a hollow semi-circular boss extrusion, six large rectangular cut-extrudes were patterned vertically along the shell wall. These open windows perform two vital submerged functions: they substantially reduce the structural mass of the 3D-printed cage, and they allow water to flow freely through the cage walls during jaw closure so that hydrodynamic bow waves do not push the neutrally buoyant jellyfish out of reach.

Connecting the two semi-cylindrical cages along their rear spine are two interlocking door-style hinges (Upper Hinge and Lower Hinge). Each hinge consists of a female double-knuckle clevis block (**Hinge Part 1**) and a mating male knuckle block with an integrated vertical cylindrical pin running through the center (**Hinge Part 2**), providing rigid coaxial alignment across the entire height of the cage.

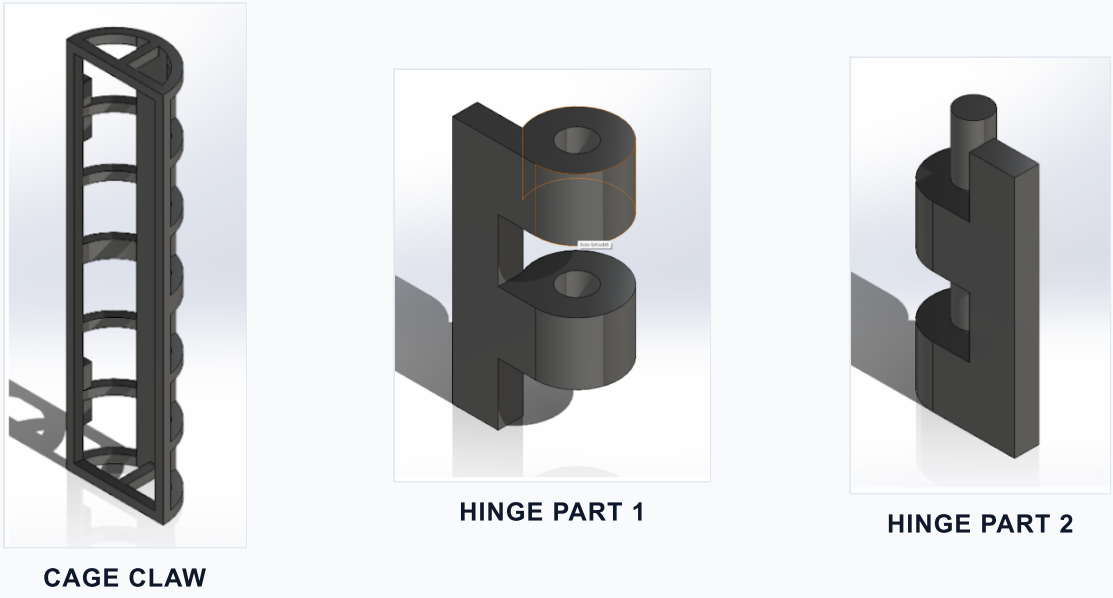


Figure 9: SOLIDWORKS part models of the **Cage Claw** (left) with six hydrodynamic weight-reduction cutouts, and the interlocking rear door-style hinge components: **Hinge Part 1** (center) and **Hinge Part 2** (right).

2.5 Modular Quick-Release Latch System

To ensure that the Servo Housing and the Gearbox remain rigidly coupled against axial separation forces generated by the linear rack—while still permitting rapid field disassembly and modular claw interchangeability—a pair of snap-fit mechanical latches was engineered for the top and bottom housing seams. Each latch assembly comprises two mating blocks:

- **Latch 1 (Latch Insertion Block):** Features an internal cantilevered beam with a ramped hook tip extending forward from a protective rectangular shroud. Designed to flex elastically downward during insertion, the angled latch tongue snaps upward into an internal locking groove inside the mating receptacle once fully seated, preventing axial pull-out.
- **Latch 2 (Latch Reception Block):** Houses the internal locking groove and incorporates an integrated vertical push-button actuator on its top surface. Depressing the top button deflects the cantilevered snap-arm of Latch 1 downward out of the retention groove, allowing the Gearbox module to slide cleanly off the Servo Housing.

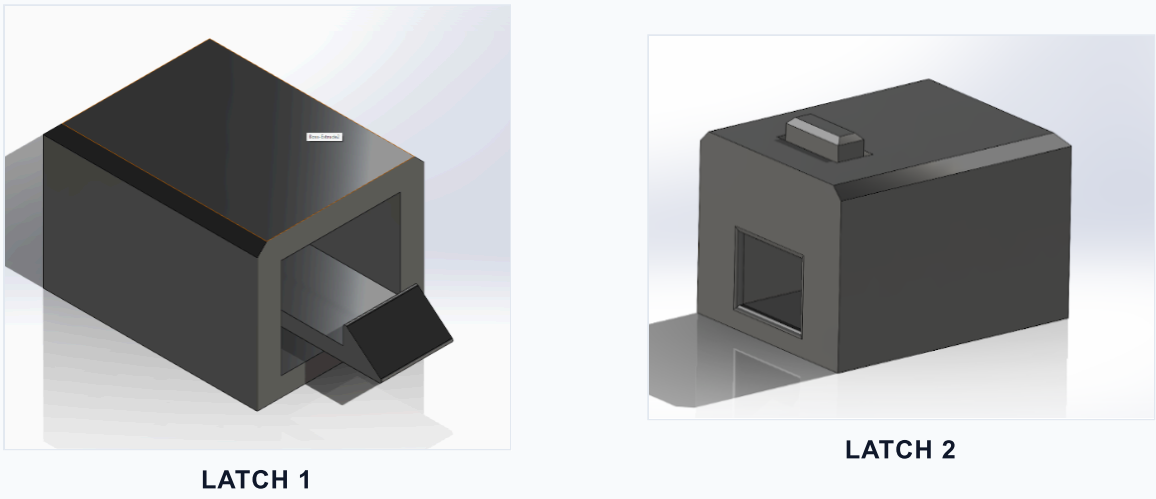


Figure 10: SOLIDWORKS part models of the modular quick-release coupling: **Latch 1** (left, Insertion Block) with its cantilevered snap hook, and **Latch 2** (right, Reception Block) featuring an integrated top push-button release.

2.6 Assembly Mating Architecture & Material Selection

In the master SOLIDWORKS assembly, all 30 components were integrated using a structured hierarchy of geometric and mechanical mates to validate component fit and motion transfer (Erlingsson et al., 2016):

1. **Rack-to-Housing Guidance:** The Dual-Axis Linear Rack is constrained within the Bottom Servo Housing channel using coincident planar mates on its lower face and side guide walls, leaving one translational degree of freedom along the longitudinal axis.
2. **Gearbox Sub-Assembly & Rotary Shafts:** The two Vertical Rotary Arm shafts are mated concentrically with the internal bearing bosses of the Bottom Gearbox and the cut-extruded bores of the Top Gearbox. Each 6 mm Spur Gear is locked concentrically and coincidentally to its corresponding vertical shaft, while the Top Rotary Arms mate onto the recessed square sockets.
3. **Housing Coupling & Latch Engagement:** The Gearbox is mated flush against the forward neck of the Servo Housing, and the two pairs of Latch Insertion and Reception blocks are mated across the upper and lower housing seams.
4. **Mechanical Tooth & Linkage Mates:** Rack-and-pinion mechanical mates link the 10 mm Servo Pinion and the dual 6 mm Rotary Arm Gears to the orthogonal tooth planes of the Linear Rack, while concentric and coincident mates join the three-layer Additional Arms, Caged Claws, and rear interlocking hinges.

3.0 Engineering Analysis, Design Evaluation & Conclusions

3.1 Additive Manufacturing Practicality & Tolerance Evaluation (DFM/DFA)

Overall, the completed 30-component CAD assembly successfully realized the initial conceptual architecture for a non-destructive, waterproof *Medusa* capture mechanism. Approximately 40 engineering hours were invested across conceptual sketching, dimensional research on the ROV mounting envelope and target *Medusa* geometry, parametric part modeling, and full assembly mating. Evaluating the final design for real-world fabrication highlights several key Design for Manufacturing and Assembly (DFM/DFA) insights:

- **3D Printer Resolution & Small-Feature Fidelity:** Several transmission and coupling components—specifically the 18-tooth spur gears, the dual-axis rack teeth, and the compliant cantilever beam inside Latch 1—contain relatively small, intricate features. Fabricating these parts with functional clearances requires a well-calibrated fused deposition modeling (FDM) or stereolithography (SLA) 3D printer capable of holding $\pm 0.10\ mm$ dimensional tolerances.
- **Waterproof Seal Accuracy:** At compact component scales, achieving a reliable waterproof seal across the split Servo Housing, Gearbox cover, and rotary shaft pass-throughs requires tight flatness tolerances along the gasket compression grooves and the addition of dynamic rotary shaft O-rings around the vertical rotary arms.
- **Parametric CAD Discipline:** A major engineering lesson reinforced during the modeling of the gear teeth and linkage arms is the importance of establishing global design tables or linked master dimensions prior to feature completion. Modifying gear pitch or linkage lengths late in the design tree often necessitates rebuilding dependent sketches and re-establishing assembly mates from scratch.

3.2 Kinematic Stability Analysis & Future Design Improvements

While the mechanism performs the intended encirclement motion geometrically, critical kinematic evaluation identified two areas for refinement prior to physical underwater deployment:

- **Gear Tooth Profile & Arm Length Optimization:** Because the custom gear teeth were approximated using line-and-arc sketches rather than true involute curves, conducting a dynamic SOLIDWORKS Motion Study requires minor dimensional tuning of the tooth clearance (backlash) and rotary arm center-to-center length to guarantee bind-free meshing throughout the full stroke.
- **Prevention of Elbow Hinge Hyperextension (Toggle Lock):** During wide-open jaw states, the symmetrical Additional Arms and three-layer elbow hinges can approach a collinear toggle position (hyperextension). If the elbow joint hyperextends past $180°$, subsequent retraction of the rotary arms can lock the cage in the open position rather than folding it inward. This kinematic instability can be resolved in future iterations by integrating a rigid vertical guide rod or mechanical travel stop extending from the front face of the Gearbox to bear against the inner face of the elbow hinge, preventing over-center hyperextension.

4.0 References

1. Bjartmar Freyr Erlingsson, Ingólfur Hreimsson, Páll Indriði Pálsson, Sigurður Jóhann Hjálmarsson, and Joseph Timothy Foley (2016). *Axiomatic Design of a Linear Motion Robotic Claw with Interchangeable Grippers*. Procedia CIRP, Volume 53, Pages 213–218, ISSN 2212-8271. **https://doi.org/10.1016/j.procir.2016.07.006**

2. MATE ROV Competition (2025). *Marine Advanced Technology Education (MATE) Remotely Operated Vehicle Competition Technical Guidelines & Mission Specifications*. Accessed May 22, 2025. **https://materovcompetition.org**