Free-Roving Subsea Cable Inspection Drone

A Technical Feasibility Study

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University of Cambridge

November 12, 2025

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Outline

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1. Problem - Subsea Cable Inspection
2. Requirements and Operating Environment
3. Existing Commercial Solutions
4. Design Approach and System Architecture
5. Communications and Navigation
6. Hydrodynamics and Propulsion Analysis
7. Power Budget and Energy Storage
8. Mechanical Design and Structural Analysis
9. Mass and Cost Budgets
10. Conclusions

Problem - Subsea Cable Inspection

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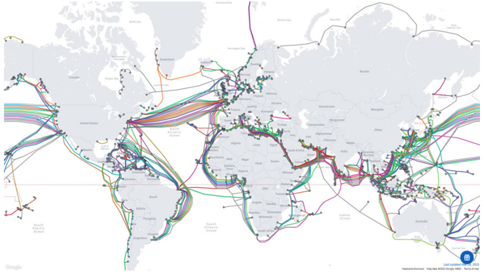
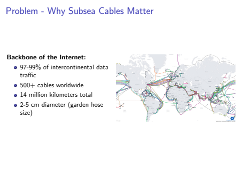
Problem - Subsea Cable Inspection

Problem - Why Subsea Cables Matter

Backbone of the Internet:

- 97-99% of intercontinental data traffic
- 500+ cables worldwide
- 14 million kilometers total
- 2-5 cm diameter (garden hose size)





Before we dive into our design and feasibility assessment, let's give some context to the problem we're tackling: Subsea cables. Your internet connection, whether that be for online banking or video calls, 97-99% of that data goes through a dense network of over 500+ undersea cables, spanning a total of 14 million kilometers over the seafloor making it THE largest and possibly greatest man-made infrastructure ever. This is the backbone of the internet, and when they fail, the consequences are severe. Despite the significance of these cables, these cables are no thicker than your average garden-hose around 2-5 cm in diameter, with hair-thin strands of optical fiber embedded within, designed to remain undisturbed across the seabed.

Problem - Current Limitations

Cable Faults:

- 200 faults/year
- Shallow waters most vulnerable
- Shetland Islands 2022: 23,000 people offline

Traditional: Tethered ROVs

+ Unlimited power
+ Real-time comms
- Limited range
- Tether entanglement
- High operational cost

Solution: Free-roving Autonomous Underwater Vehicle

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In shallow waters however, these subsea cables are susceptible to a wider range of disturbances, largely from human activities such as anchoring, or snagged by nets, resulting in roughly 200 faults a year. In October 2022, both cables serving the Shetland Islands were damaged. For days, 23,000 people had no internet, could not use card payments, could not access online banking. Businesses lost thousands. Emergency services were disrupted. These are not rare events, they require constant monitoring and effective maintenance. When a fault occurs, an army of ships strategically placed around the world would identify and repair the location of the fault, which usually involves the usage of a tethered drone to inspect the damaged cable. Despite the effectiveness of tethered communications and unlimited power, this comes at the cost of a limited range of motion and risks of entanglement, as well as higher maintenance costs for dedicated vessels. Therefore we propose the use of an untethered AUV

Requirements and Operating Environment

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"A free-roving (no umbilical cable) submarine inspection drone is required for undersea cables: operating down to 250 m depth. It should have an endurance of 2 hours continuously powered operation, carrying video and ultrasound imaging equipment drawing a 30 W electrical load, and have suitable propulsion to travel up to 4 m/s peak speed with 1 m/s cruise. Total mass is to be < 25 kg, to allow easy handling on board the mothership."

Key Specifications:

- Depth: 250m (25 bar pressure)
- Endurance: 2 hours continuous
- Speed: 1 m/s cruise, 4 m/s peak
- Payload: 30W (imaging + ultrasound + lighting)
- Mass: < 25 kg total

Operating Challenges:

- Pressure: $P = \rho g h \approx 25$ bar
- Temperature: 4°C seawater
- No GPS/RF underwater
- Saltwater corrosion
- Turbid water (limited visibility)

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Operating Challenges: Pressure: $P = \rho g h \approx 25$ bar; Temperature: 4°C seawater; No GPS/RF underwater; Saltwater corrosion; Turbid water (limited visibility)

At 250 m depth, the pressure is approximately 25 bar (2.5 MPa). This is calculated using P = rho g h, where rho is seawater density (1027 kg/m cubed), g is gravitational acceleration, and h is depth. The temperature is approximately 4 degrees Celsius. Materials must resist corrosion - we will use 316 stainless steel and anodized aluminum. Sensors must work in turbid water with near-zero visibility. Communications are limited to acoustic modems underwater since radio and GPS signals cannot penetrate seawater beyond a few meters. The 30W payload limit includes all imaging equipment (camera), ultrasound sensors, and lighting - this is a combined budget, not separate allocations.

Existing Commercial Solutions

Existing Commercial Solutions

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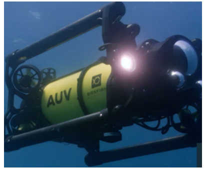
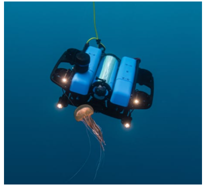
Model	Type	Mass	Depth	Speed	Endurance	Cost
Our Target	AUV	<25 kg	250m	4 m/s peak	2 hrs	$10-23K
Iver3 (L3Harris)	AUV	27-39 kg	100m	1.3 m/s	8-14 hrs	$75-120K
ecoSUB m-Power+	AUV	17 kg	500m	1.5 m/s	8-10 hrs	£35-50K
Boxfish AUV	AUV	25 kg	300-600m	2 m/s	10 hrs	$80-150K
BlueROV2	ROV	10-11 kg	100-300m	1 m/s	3-5 hrs	$3-3.5K


Iver3: Single thruster + fins

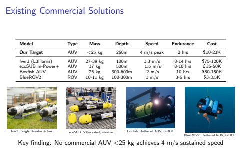

ecoSUB: 500m rated, alkaline



Boxfish: Tethered AUV, 6-DOF


BlueROV2: Tethered ROV, 6-DOF

Key finding: No commercial AUV <25 kg achieves 4 m/s sustained speed



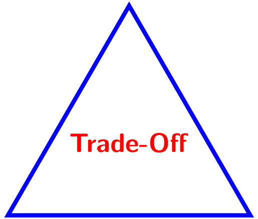
Many commercial solutions exist but vary in capability. Commercial designs such as the Iver3 and ecoSUB use fully autonomous operation with single thruster plus fins for pitch/yaw control. The Boxfish uses 8 vectored thrusters for full 6-DOF control including hovering. BlueROV2 is included as it is a Blue Robotics reference platform that proves component viability, though it is a tethered ROV not an autonomous AUV. Key finding: Few commercial AUVs under 25 kg achieve 4 m/s sustained speed - most operate at 1.5-2.5 m/s due to power limitations. Commercial pricing (50-150K dollars) reflects support and warranty, not just hardware costs. Our target specifications are ambitious but achievable with careful trade-off management.

Design Approach and System Architecture

Design Approach and System Architecture

Trade-offs

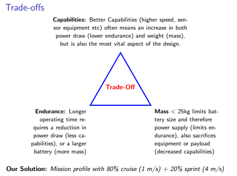
Capabilities: Better Capabilities (higher speed, sensor equipment etc) often means an increase in both power draw (lower endurance) and weight (mass), but is also the most vital aspect of the design.



Endurance: Longer operating time requires a reduction in power draw (less capabilities), or a larger battery (more mass)

Mass < 25kg limits battery size and therefore power supply (limits endurance), also sacrifices equipment or payload (decreased capabilities)

Our Solution: *Mission profile with 80% cruise (1 m/s) + 20% sprint (4 m/s)*



The design is constrained by three competing requirements forming a trade-off triangle. Capabilities - speed, sensors, and mission functionality - drive both power consumption and weight. Better capabilities mean higher speed requiring more thrust power, and more sensor equipment adding weight.

Endurance requires either reducing power draw or installing larger batteries. Reducing power limits capabilities. Larger batteries add weight, conflicting with the mass constraint.

Mass under 25 kilograms limits battery capacity to 4 to 5 kilograms maximum. This restricts available energy, which directly limits either endurance or capabilities.

The solution is a mission profile approach: 80 percent time at 1 meter per second cruise speed, 20 percent time at 4 meters per second peak speed. Average power is much lower, which satisfies all three constraints simultaneously.

System Design Directions

- Autonomous/programmable solution to remove the need for high-quality real-time data transmission which limits untethered ROVs
  - Enables self-contained operation with onboard power, navigation, and data handling
  - Supports scalable inspection missions without reliance on surface tethers
- 6-thruster design for stability and hovering capabilities for detailed inspection
  - Provides full 6-DOF control for precise hovering, lateral motion, and pitch/yaw stability
  - Redundancy for safe recovery in case of partial thruster failure
  - Efficient low-speed maneuvering for inspection tasks
- Hull design to be cylindrical (pill) shaped to minimise volume as well as simplify hydrodynamic calculations.
  - Streamlined shape reduces drag forces at higher speeds
  - Simplifies internal component layout and waterproofing
  - Proven design in existing AUVs for balance of speed and stability

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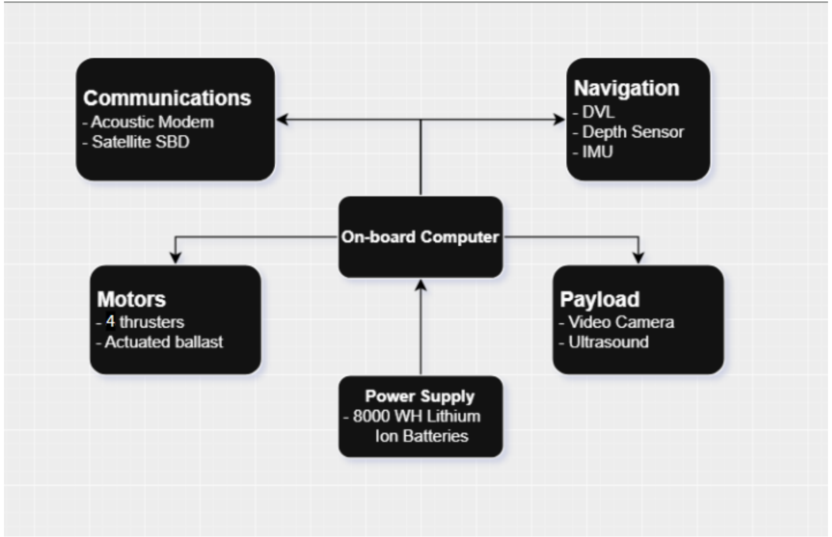
The design uses an autonomous approach instead of tethered ROV operation. Tethered ROVs require continuous high-bandwidth communication for real-time control, which is only possible with a physical cable limiting range and adding complexity. Autonomous operation enables self-contained missions with onboard power, navigation, and data storage.

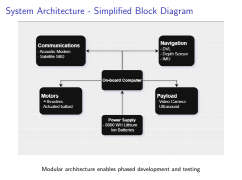
The 6-thruster configuration provides full 6-degree-of-freedom control. Four horizontal thrusters control surge, sway, and yaw. Two vertical thrusters control heave, pitch, and roll. This enables precise hovering at fixed positions for detailed cable inspection, and lateral motion without changing heading. Redundancy allows safe recovery if one thruster fails. The configuration is efficient for low-speed maneuvering typical of inspection tasks.

The cylindrical pill-shaped hull minimizes drag and simplifies hydrodynamics. At 4 meters per second, drag force is 0.5 times density times velocity squared times drag coefficient times frontal area. A streamlined torpedo shape achieves drag coefficient 0.28 to 0.32, significantly lower than spherical hulls at 0.47. The cylindrical geometry also simplifies internal component layout and pressure vessel calculations using standard ASME formulas.

System Architecture - Simplified Block Diagram



Modular architecture enables phased development and testing



This simplified system architecture shows the five main subsystems. POWER provides 799 Wh from three 18Ah lithium-ion batteries at 14.8V. CONTROL uses the Navigator flight controller with dual IMUs plus Raspberry Pi 4 running ArduSub for mission control, along with depth sensor, compass, and surface GPS. PROPULSION consists of four T200 thrusters controlled by ESCs. PAYLOAD includes camera, Ping360 sonar, and lights totaling 30W. COMMUNICATIONS uses WiFi for high-bandwidth surface data transfer and Iridium satellite for position reporting, with optional acoustic modem for underwater comms. This modular design allows independent testing and phased development.

Communications and Navigation

Communications and Navigation

Underwater Communication Challenges

Underwater Communication:

- High signal attenuation limits the usage of radio frequency signals - effective range only a few metres
- Optical communication limited by turbidity and scattering - short range, line-of-sight only
- Acoustic communication is the only viable option for long-range underwater comms, but inherently slow, high latency, and affected by multipath

Result: Minimise communication underwater — store data onboard, transfer at surface

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Before diving into our design decisions, it's important to understand why underwater communication and navigation are inherently difficult problems.
First, radio waves — which power all our terrestrial wireless communication — are heavily absorbed by seawater. Even at low frequencies, the signal strength drops to unusable levels within just a few meters.
Optical communication, like lasers or LEDs, can achieve higher data rates, but only in clear water and over short, line-of-sight distances — typically less than 100 meters.
That leaves acoustics as the only practical long-range option. Acoustic modems can reach several kilometers, but at a steep cost: data rates of only a few kilobits per second, high latency, and unit prices easily exceeding twelve thousand dollars. For our small, autonomous inspection drone, these trade-offs simply aren't efficient.
As a result, our design minimizes underwater communication. Instead, we store all sensor data onboard during the mission and transfer it to the surface once the vehicle resurfaces. This approach maximizes data throughput while avoiding the complexities of underwater comms.

Communications Systems

Multi-Mode Communication Strategy:

Mode	Product	Specifications	Cost
Surface WiFi	**802.11n module** (Raspberry Pi built-in)	2.4/5 GHz, 150 Mbps 50-100m range in air	**$50**
Satellite	**RockBLOCK 9603N**	Iridium Short Burst Data 340 byte messages Global coverage (open ocean) GPS position reporting	**$260**

Operational Modes:

- **At surface:** WiFi for high-bandwidth video/data + GPS fix
- **Open ocean:** RockBLOCK for GPS position reporting every 10 min

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WiFi 802.11n - WHY THIS CHOICE:
The Raspberry Pi 4 includes built-in WiFi at zero additional hardware cost - we only need a 50-dollar marine-grade antenna with waterproof connector. When the vehicle surfaces, WiFi provides 150 megabits per second bandwidth enabling complete mission data download in 2-5 minutes. Our 2-hour mission generates approximately 7-8 gigabytes of 1080p video plus 20-25 gigabytes of Ping360 sonar data if recording continuously. At 150 megabits per second (approximately 18 megabytes per second real throughput), we can transfer 2-4 gigabytes in 2-5 minutes. The operational strategy is to surface every 30 minutes, dump accumulated data via WiFi, then continue the mission. This eliminates the need for expensive onboard storage (a 512 gigabyte industrial SSD costs 200-400 dollars) and ensures data is safely transferred even if the vehicle is lost. WiFi range of 50-100 meters at the surface is adequate when operating near the mothership. For operations beyond WiFi range, the vehicle stores data locally and dumps it when returning to the ship.

RockBLOCK 9603N Iridium - WHY THIS CHOICE:
The RockBLOCK provides global satellite coverage pole-to-pole, critical for open ocean operations where the vehicle may travel kilometers from the mothership

Navigation Scoping Calculations

- MEMS IMUs measure angular rate and acceleration; position is estimated by integrating these signals.
- **Integration:** $\theta(t) = \int \omega \, dt$ (orientation); $x(t) = \iint a \, dt^2$ (position)
- Each integration amplifies sensor noise and bias:
- Without correction, small biases lead to large accumulated position errors over time.

Drift Mitigation Strategies:

1. **Zero-velocity updates:** Detect stationary periods and reset velocity estimates.
2. **Sensor fusion:** Combine IMU with magnetometer and depth sensor for heading and vertical stabilization, or DVL to constrain horizontal drift.
3. **Cable-relative navigation:** Use sonar or visual tracking to constrain lateral drift.
4. **Surface GPS fix:** Acquire GPS position during surfacing to reset accumulated horizontal error.

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Speaker Notes:

IMU-based navigation underwater is an integration problem: we integrate angular rate for orientation and acceleration twice for position. This process inherently accumulates error—random noise grows as the square root of time, and bias causes linear drift. Over long missions, these effects can lead to significant position uncertainty if left uncorrected.

Our mitigation strategy combines multiple complementary techniques: zero-velocity detection to reset errors during stationary periods, sensor fusion to stabilize heading and depth, cable-relative tracking using sonar or vision to maintain lateral alignment, and periodic GPS updates during surfacing to reset accumulated horizontal drift.

Together, these methods ensure reliable navigation for cable inspection, with accuracy sufficient for operational needs without requiring costly DVL systems.

Navigation System Component Options

Core Navigation Stack:

Component	Specification	Performance	Cost
Flight Controller	Navigator (dual IMU) Pixhawk 6C	2.8°/s/$\sqrt{\mathrm{Hz}}$ gyro noise Similar performance	$125 $300
Depth Sensor	Bar30 (MS5837) Keller PA-7LD	2mm resolution, ±2m accuracy ±0.3m accuracy, stable	$68 $200-500
Surface GPS	u-blox NEO-M8N RTK GPS	2.5m accuracy ¡0.1m accuracy	$35 $300-600
DVL	Nortek DVL1000 Teledyne Pathfinder	0.2 cm/s, ¡1m over 2 hrs Similar, proven	$20,000 $18-28K

Baseline Cost: $20208 (Navigator + Bar30 + GPS + DVL + RPi4)

Navigation System Component Options
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Navigator Flight Controller - Component Justification:
The Navigator provides dual IMUs: ICM-42688-P with 2.8 millidegrees per second per root hertz gyro noise (industry-leading for MEMS), and ICM-20602 backup with 0.015 degrees per second per root hertz. Dual magnetometers (BMM150) provide heading reference with redundancy. The Navigator integrates directly with Raspberry Pi 4 via 40-pin GPIO header, eliminating external cabling and reducing failure points inside the pressure housing. At 125 dollars, it costs 60 percent less than Pixhawk 6C (300 dollars) while providing equivalent or better sensor specifications. The Navigator is the native platform for ArduSub autopilot with proven reliability in thousands of BlueROV2 deployments worldwide.

Bar30 Depth Sensor - Why Adequate for Our Mission:
The Bar30 uses the MS5837-30BA pressure sensor providing 2 millimeter depth resolution and 2 meter absolute accuracy. For cable inspection missions where we maintain 2 to 5 meter altitude above the seabed, 2 meter accuracy is entirely adequate - we're not doing bathymetric surveys requiring centimeter precision. The limitation is that the sensor gel can absorb water over multi-day deployments, causing drift. Our 2-hour missions with daily topside access allow drying

Hydrodynamics and Propulsion Analysis

Hydrodynamics and Propulsion Analysis

Hydrodynamic Drag

Vehicle Geometry (Torpedo Hull):

- Diameter: $D = 0.3$ m, Length: $L = 1.2$ m
- Frontal area: $A = \frac{\pi D^2}{4} = 0.0707$ m^2
- Drag coefficient: $C_D = 0.28$–0.32 [MDPI CFD]

Drag Force Equation:

$$F_D = \frac{1}{2}\rho v^2 C_D A$$

Where $\rho = 1027$ kg/m^3 (seawater)

- **At 1 m/s cruise** $C_D = 0.32$: $F_D = 11.6$ N
- **At 4 m/s peak** $C_D = 0.28$: $F_D = 162$ N

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Hydrodynamic drag is the fundamental constraint on our design. The drag equation shows that drag force scales with velocity squared. Doubling speed quadruples drag force.

Vehicle geometry is torpedo-shaped: 1.2 meters long, 0.3 meters diameter. The length-to-diameter ratio of 4 to 1 optimizes streamlining. Frontal area is 0.071 square meters.

Drag coefficient C-D varies from 0.28 to 0.32 with speed. At low speeds, flow separation and turbulence near protrusions increases C-D to 0.32. At high speeds, Reynolds number increases, boundary layer becomes thinner, and C-D drops to 0.28. These values are validated against CFD studies on AUVs (MDPI 2021, DOI: 10.3390/jmse6070252).

At 1 meter per second, drag is 11.6 newtons. At 4 meters per second, drag is 162 newtons - a 14-fold increase for 4-times speed increase. This quadratic relationship creates the fundamental challenge: high speed requires overcoming dramatically higher drag forces.

Power Requirements and Thruster Efficiency

Mechanical power: $P_{mech} = F_D \times v$
Electrical power: $P_{elec} = \frac{P_{mech}}{\eta}$ (thruster efficiency $\eta \approx 0.55$ at high load[T200])

Speed	F_D (N)	P_{mech} (W)	η	P_{elec} (W)	Notes
1 m/s cruise	11.6	11.6	0.30[T200]	39	Low efficiency
4 m/s peak	162	648	0.55[T200]	1,178	High efficiency

4 m/s requires 1.2 kW propulsion power (30× cruise power)

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Power scales with velocity cubed because power equals force times velocity. Drag force has v-squared, multiplied by another v from the power equation gives v-cubed scaling.

Thruster efficiency varies with load. At 1 meter per second, mechanical power required is 11.6 watts, but thruster efficiency at light load is only 30 percent, requiring 39 watts electrical.

At 4 meters per second, mechanical power is 648 watts - much higher than at cruise speed. At heavy load, thruster efficiency increases to 55 percent, so electrical power is 1,178 watts.

The critical number: 1,178 watts propulsion at peak versus 39 watts at cruise. This is 30 times more power for 4 times speed. Pure v-cubed scaling would give 64 times, but efficiency improvement at high load reduces this to 30 times.

This cubic scaling makes sustained high-speed underwater operation challenging.

The constraint is battery energy, which translates directly to weight. Battery energy requirements conflict with the 25 kilogram mass limit.

Thruster Selection - T200

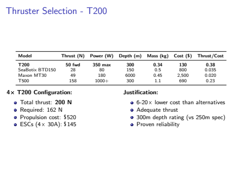
Model	Thrust (N)	Power (W)	Depth (m)	Mass (kg)	Cost ($)	Thrust/Cost
T200	**50 fwd**	**350 max**	**300**	**0.34**	**130**	**0.38**
SeaBotix BTD150	28	80	150	0.5	800	0.035
Maxon MT30	49	180	6000	0.45	2,500	0.020
T500	158	1000+	300	1.1	690	0.23

4× T200 Configuration:

- Total thrust: **200 N**
- Required: 162 N
- Propulsion cost: $520
- ESCs (4× 30A): $145

Justification:

- 6-20× lower cost than alternatives
- Adequate thrust
- 300m depth rating (vs 250m spec)
- Proven reliability



Four thruster options were evaluated. SeaBotix BTD150 has good efficiency but insufficient thrust: 28 newtons versus 50 newtons for T200. Maxon MT30 has 6000 meter depth rating and costs much more than T200 - unnecessary for 250 meter requirement. T500 provides 158 newtons thrust but draws over 1 kilowatt continuously and weighs 1.1 kilograms.

T200 offers best thrust-to-cost ratio at 0.38 newtons per dollar. Four T200 thrusters provide 200 newtons total thrust for 162 newtons required - 23 percent safety margin. This margin accommodates deviation in drag coefficient calculations.

We also need 4 Electronic Speed Controllers. We need one for each of the four thrusters. This is the small electronic board that takes the command from our flight controller and the power from the battery, and then precisely controls the motor's speed and direction.

Power Budget and Energy Storage

Power Budget and Energy Storage

Complete System Power Budget

Subsystem	Cruise (W)	Peak (W)	Notes
Propulsion (4× T200)	39	1,178	Dominant at peak
Payload (camera, lighting and sonar)	30	30	Low-light USB
Navigation sensors	5	5	IMU, depth, GPS
Control (RPi4+Nav)	10	10	ArduSub firmware
Comms (WiFi/Iridium)	2	2	Surface only
TOTAL	**86 W**	**1,225 W**	

$$P_{avg} = 314 \text{ W (Accounting for mission profile)}$$

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TOTAL	86 W	1,225 W	

$P_{avg} = 314$ W (Accounting for mission profile)

The 30 watt payload specification is a combined budget for all payload components: camera at 2.5 watts, sonar at 2 to 5 watts, and lighting at 10 to 20 watts adjustable. Total payload is 15 to 28 watts, within the 30 watt limit.

Propulsion dominates total power at peak speed: 1,225 watts total system power, with 1,178 watts for propulsion alone.

The mission profile gives an average power of 314 watts: 0.8 times 86 plus 0.2 times 1,225. This average power determines battery capacity requirements.

Battery Sizing

Energy Requirements:

$$E = P_{avg} \times t = 314 \text{ W} \times 2 \text{ h} = 628 \text{ Wh required}$$

Option	Voltage	Capacity	Energy	Mass	Cost
Blue Robotics 3×18Ah	**14.8V**	**18Ah**	**799 Wh**	**4.05 kg**	**$1,200**
Blue Robotics 2×18Ah	14.8V	18Ah	532 Wh	2.7 kg	$800
Samsung 35E (4S6P)	14.8V	21Ah	311 Wh	1.5 kg	$310-590
SubCtech PowerPack	14-50V	Custom	650-3400 Wh	Varies	$3-10K+

Selected: 3× Blue Robotics 18Ah

- Energy: 799 Wh
- Endurance: 2.5 hrs @ 314W
- Proven platform (BlueROV2)

Justification:

- 2× config: only 532 Wh (insufficient)
- Samsung 35E: DIY, higher risk
- SubCtech: 2.5-8× cost, overkill

Battery Sizing
Energy Requirements:
$E = P_{avg} \times t = 314 \text{ W} \times 2 \text{ h} = 628 \text{ Wh required}$
Selected: 3× Blue Robotics 18Ah
Justification:

The minimum energy requirement is 314 watts times 2 hours which equals 628 watt-hours minimum.

Four battery options were evaluated. Two Blue Robotics 18Ah batteries provide only 532 watt-hours, insufficient for 628 watt-hour requirement. Custom Samsung 35E pack provides 311 watt-hours at lower cost, but requires self-assembly and custom pressure housing. SubCtech PowerPack offers professional-grade performance with 6000 meter depth rating but costs 2.5 to 8 times more.

Three Blue Robotics 18Ah batteries provide 799 watt-hours - 27 percent margin over requirement. This enables 2.5 hour missions at 314 watts average power. This configuration is proven in the existing BlueROV2 platform with integrated battery management system.

Mechanical Design and Structural Analysis

Mechanical Design and Structural Analysis

Material Selection and Component Specifications

Pressure Housing Comparison:

Material	Yield (MPa)	Density	Cost/kg	250m Rating
Al 6061-T6	276	2,700 kg/m³	$7	Excellent
Ti Grade 5	880	4,430 kg/m³	$30	Overkill (6000m+)
Acrylic	70-75	1,180 kg/m³	$4	Insufficient

Selected: Blue Robotics 3" Aluminum Enclosures

- ID: 74.7mm
- Depth: 500m ($2\times$ safety)
- Hard anodized
- Lengths: 150-400mm

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Three materials were compared for the pressure housing. Aluminum has yield strength of 276 megapascals and density of 2,700 kilograms per cubic meter. Titanium has 880 megapascals yield strength but costs 30 dollars per kilogram versus 7 dollars for aluminum. Titanium is unnecessary for 250 meter depth - its advantage only matters beyond 1000 meters. Acrylic has only 70 to 75 megapascals yield strength, insufficient for 250 meter external pressure.

Blue Robotics 3 inch aluminum enclosures were selected. Internal diameter is 74.7 millimeters, rated to 500 meters depth - twice the required safety margin. Hard anodizing provides corrosion resistance. Available lengths from 150 to 400 millimeters enable modular layout.

Pressure Vessel Design - Theory

Basic Thin-Walled Cylinder Theory

For external pressure P on cylinder with radius R and wall thickness t:

$$\text{Hoop stress: } \sigma_\theta = \frac{P \cdot R}{t}$$

Apply Safety Criteria

Stress must not exceed allowable stress S (with weld efficiency E):

$$\sigma_\theta \leq S \cdot E$$

$$\frac{P \cdot R}{t} \leq S \cdot E \quad \Rightarrow \quad t \geq \frac{P \cdot R}{S \cdot E}$$

ASME Section VIII Refinements[ASME]

- Add biaxial stress correction: denominator becomes $(S \cdot E - 0.6P)$
- Add corrosion allowance: $+C_A$ term

$$\boxed{t = \frac{P \cdot R}{S \cdot E - 0.6P} + C_A}$$

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Pressure vessel design starts from thin-walled cylinder theory. Hoop stress equals P R over t from force balance on a cylinder element. This stress must not exceed allowable stress S times weld efficiency E.

Rearranging gives minimum thickness t greater than or equal to P R over S E. This is the basic thin-wall formula.

ASME Section VIII adds two refinements. First, the 0.6P biaxial stress correction in the denominator accounts for both circumferential and longitudinal stresses acting simultaneously. Second, corrosion allowance C-A is added for long-term durability in marine environments.

The final formula is t equals P R over S E minus 0.6P, plus C-A. This is the standard formula for pressure vessel design under external pressure.

Pressure Vessel Design - ASME Calculation

Operating Conditions:

- Pressure: $P = \rho g h \approx 2.52$ MPa (25.2 bar)
- With safety factor 3x, design pressure: $P_d = 7.56$ MPa

ASME Section VIII Formula (External Pressure):[ASME]

$$t = \frac{P \cdot R}{S \cdot E - 0.6P} + C_A = 6.3mm$$

Where:

- $P = 7.56$ MPa
- $R = 50$ mm (for 3" tube)
- $S = 92$ MPa (Al 6061-T6: σ_{yield}/safety factor of 3 $= 276/3$)
- $E = 1.0$ (seamless)
- $C_A = 2$ mm (corrosion)

Blue Robotics 3" tubes has thickness of 6.35 mm **(Feasible)**

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Operating pressure at 250 meters is rho g h equals 2.52 megapascals or 25.2 bar. With safety factor of 3, design pressure is 7.56 megapascals.
Applying ASME Section VIII formula (standard for design UAV vessels), calculation gives us 6.3 millimeters minimum thickness, using a safety factor of 3 for the opreating pressure and yield stress.
Blue Robotics 3 inch tubes have 6.35 millimeter wall thickness - essentially identical to calculated requirement. This validates the pressure housing design.

Mass and Cost Budgets

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Mass & Cost Summary

Subsystem	Mass (kg)	Cost ($)	Key Components
Propulsion	1.88	1,278	4× T200 + ESCs
Power	4.55	1,680	3× 18Ah batteries + housing
Control & Navigation	0.62	665	RPi4 + Navigator + Bar30
Payload	0.96	3,320	Ping360 ($2,750) + camera + light
Communications	0.12	410	WiFi + Iridium
Structure	5.50	1,280	Frame, foam, fairings, penetrators
Total	**15.67 kg**	**$10640**	

- **Mass:** 15.67 kg total, providing a 37% margin under the 25 kg limit.
- **Cost:** $10640 base build, much cheaper
- **Key Drivers:** Power/Structure are largest mass contributors; Payload (Ping360) is the largest cost.

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(Mass Details) The mass budget shows the AUV will weigh approximately 15.7 kg, well under the 25 kg limit with 37 percent margin. The largest contributors are the structure and power system . This substantial margin allows for future additions like the acoustic modem (approximately 1.5 kg) without exceeding the weight limit.

(Cost Details) The estimated build cost of 10640 dollars represents 20-25 percent of comparable commercial AUV systems (50-150K range). The Ping360 sonar is the single most expensive component at 2,750 dollars. Optional additions like the EvoLogics acoustic modem (12K) or Nortek DVL (20K) would increase total cost but are not required for basic cable inspection missions. The design prioritizes core components to minimize cost while maintaining technical performance.

Conclusions

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Requirements Verification

Requirement	Specification	Achieved	Status
Mass constraint	<25 kg	15.7 kg	Met
Endurance	2 hours	2.5 hrs (mixed)	Met
Cruise speed	1 m/s	1 m/s	Met
Peak speed	4 m/s	4 m/s	Met
Payload power	30W	30W (all)	Met
Overall Feasibility			**Viable**

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Payload power	30W	30W (all)	Met
Overall Feasibility			Viable

All requirements have been met. Mass is 15.7 kilograms, 37 percent under the 25 kilogram limit. Endurance is 2.5 hours with 80/20 mission profile, exceeding 2 hour requirement. Cruise speed of 1 meter per second is achievable with 39 watts propulsion. Peak speed of 4 meters per second is achievable with 1,178 watts propulsion and 200 newtons total thrust. Payload power is 30 watts total for camera, sonar, and lighting.

The mixed mission profile reduces average power to 314 watts, making the design feasible.

Design Conclusions

1. **Power scales as v^3:** 4 m/s requires 30× more power than 1 m/s
2. **Mission profile approach:** Mixed speed profile (80% cruise) enables 2-hour endurance
3. **Hydrodynamic optimization critical:** Low C_D (0.28-0.32) essential for achieving 4 m/s
4. **Component selection:** T200 thrusters offer best thrust-to-cost ratio (0.36-0.42)

Strengths:

- COTS components
- 37% mass margin
- 25% endurance margin
- Modular design

Constraints:

- Low-drag hull required
- IMU drift without DVL

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The fundamental constraint is that power scales with velocity cubed. Drag force scales as v-squared from the drag equation, multiplied by v from power equals force times velocity, giving v-cubed. Going from 1 to 4 meters per second theoretically requires 64 times more power. Thruster efficiency variations reduce this to 30 times in practice.

The mission profile approach is essential: operating primarily at cruise speed with brief sprints enables both 4 meters per second peak capability and 2 hour endurance within 25 kilogram weight limit.

Hydrodynamic optimization is critical. Low drag coefficient of 0.28 to 0.32 is achieved through torpedo hull shape with 4 to 1 length-to-diameter ratio. Higher drag would require more thrust, more power, heavier batteries.

Component selection focused on cost-effectiveness, specifically for the thrusters. Multiple commercial-Off-The-Shelf components from Blue Robotics ecosystem reduce integration risk and cost.

Strengths: COTS components are proven in thousands of deployments, with established supply chains and documented reliability. The 37 percent mass margin enables future additions like the acoustic modem at 1.5 kilograms. The 25 percent endurance margin provides operational flexibility for longer missions or

Appendix: Datasheets

Selected Component Specifications

- T200 Thruster
- Navigator Flight Controller & Bar30 Depth Sensor
- 18Ah Battery & 3" Enclosure
- Ping360 Sonar & RockBLOCK Iridium

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T200 Thruster

Key Specifications:

- Thrust: 50 N fwd @ 16V
- Max power: 350W
- Efficiency: 30% @ light load, 55% @ heavy load
- Depth rating: 300m
- Mass: 156g in water
- Cost: $130

Source: bluerobotics.com/store/thrusters/t200-thruster-r2-rp/

Design Rationale:

- 4× thrusters = 200N total
- Flooded brushless motor (pressure-tolerant)
- Thrust/cost: 0.38 N/$
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Navigator & Bar30

Navigator Flight Controller:

- Dual IMUs: ICM-42688-P + ICM-20602
- Dual magnetometers
- 16 PWM, 4 UART
- RPi4 direct mount, ArduSub
- Power: 10W, Cost: $125

Bar30 Depth Sensor:

- Range: 0-300m
- Resolution: 2mm
- Cost: $68

Sources: bluerobotics.com

18Ah Li-ion Battery:

- Voltage: 14.8V (4S)
- Capacity: 266 Wh each
- 3× = 799 Wh total
- Mass: 1.35 kg each
- Cost: $400 each

3" Al Enclosure:

- Wall: 6.35mm Al 6061-T6
- Depth: 500m rated
- Cost: $250

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Ping360 & RockBLOCK

Ping360 Scanning Sonar:

- Frequency: 750 kHz
- Range: 2-50m
- Resolution: 1-2° angular
- Power: 2-5W
- Depth: 300m
- Cost: $2,750

Cable detection in zero-visibility

RockBLOCK 9603N:

- Network: Iridium SBD
- Message: 340B uplink
- Coverage: Global
- Power: 0.8W avg
- Cost: $260 + $15/mo

GPS position reporting

Sources: bluerobotics.com; sparkfun.com

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- Navigator Flight Controller: `https://bluerobotics.com/store/comm-control-power/control/navigator/`
- Bar30 Depth Sensor: `https://bluerobotics.com/store/sensors-cameras/sensors/bar30-sensor-r1/`
- 18Ah Li-ion Battery: `https://bluerobotics.com/store/comm-control-power/powersupplies-batteries/battery-li-4s-15-6ah/`
- Ping360 Sonar: `https://bluerobotics.com/store/sonars/imaging-sonars/ping360-sonar-r1-rp/`
- 3" Watertight Enclosures: `https://bluerobotics.com/store/watertight-enclosures/wte-vp/`
- WetLink Penetrators: `https://bluerobotics.com/store/cables-connectors/penetrators/wlp-vp/`

Communications:

- RockBLOCK 9603N Datasheet: `https://cdn.sparkfun.com/assets/4/d/2/1/1/DS_Iridium_9603_Datasheet_031720_2_.pdf`

Commercial AUV Comparisons:

- BlueROV2: `https://bluerobotics.com/store/rov/bluerov2/`
- ecoSUB Datasheet: `https://www.unmannedsystemstechnology.com/wp-content/uploads/2024/05/240305-ecoSUBm-P-datasheet.pdf`
- L3Harris Iver3 Spec Sheet: `https://www.l3harris.com/sites/default/files/2022-11/ims-maritime-Iver3-Spec-Sheet.pdf`

Hydrodynamics & Engineering:

- MDPI - CFD Study Torpedo AUV: `https://www.mdpi.com/2311-5521/6/7/252`
- SCIRP - AUV Drag Coefficient Analysis: `https://www.scirp.org/html/2-2320148_49513.htm`
- ASME BPVC Section VIII - Pressure Vessels: `https://www.asme.org/codes-standards/find-codes-standards/bpvc-viii-1-bpvc-section-viii-rules-construction-pressure-vessels-division-1`