Free-Roving Subsea Cable Inspection Drone

A Technical Feasibility Study

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University of Cambridge

November 11, 2025

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Problem - Subsea Cable Inspection

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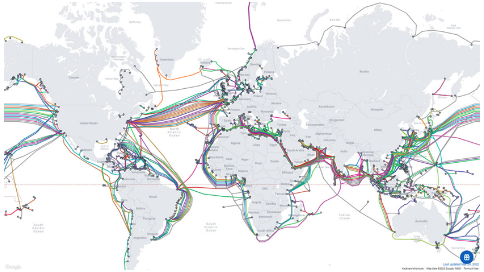
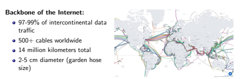
Problem - Why Subsea Cables Matter

Backbone of the Internet:

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





Problem - Why Subsea Cables Matter
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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

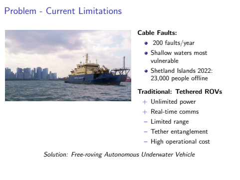
Cable Faults:

- 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



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

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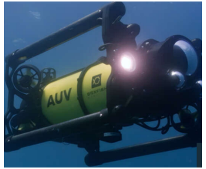
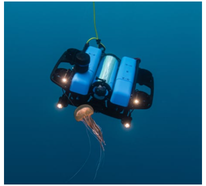
Model	Type	Mass	Depth	Speed	Endurance	Cost
Our Target	AUV	<25 kg	250m	4 m/s peak	2 hrs	$10-23K
Iver3 (L3Harris)	AUV	27-39 kg	100m	1.3 m/s	8-14 hrs	$75-120K
ecoSUB m-Power+	AUV	17 kg	500m	1.5 m/s	8-10 hrs	£35-50K
Boxfish AUV	AUV	25 kg	300-600m	2 m/s	10 hrs	$80-150K
BlueROV2	ROV	10-11 kg	100-300m	1 m/s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

Iver3: Single thruster + fins

ecoSUB: 500m rated, alkaline

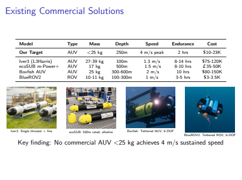


Boxfish: Tethered AUV, 6-DOF



BlueROV2: Tethered ROV, 6-DOF

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



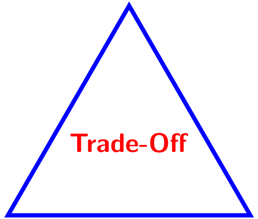
Many commercial solutions exist but vary in capability. Commercial designs such as the Iver3 and ecoSUB use fully autonomous operation with single thruster plus fins for pitch/yaw control. The Boxfish uses 8 vectored thrusters for full 6-DOF control including hovering. BlueROV2 is included as it is a 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

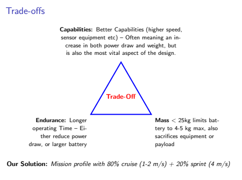
Capabilities: Better Capabilities (higher speed, sensor equipment etc) – Often meaning an increase in both power draw and weight, but is also the most vital aspect of the design.



Endurance: Longer operating Time – Either reduce power draw, or larger battery

Mass $<$ 25kg limits battery to 4-5 kg max, also sacrifices equipment or payload

Our Solution: *Mission profile with 80% cruise (1-2 m/s) + 20% sprint (4 m/s)*



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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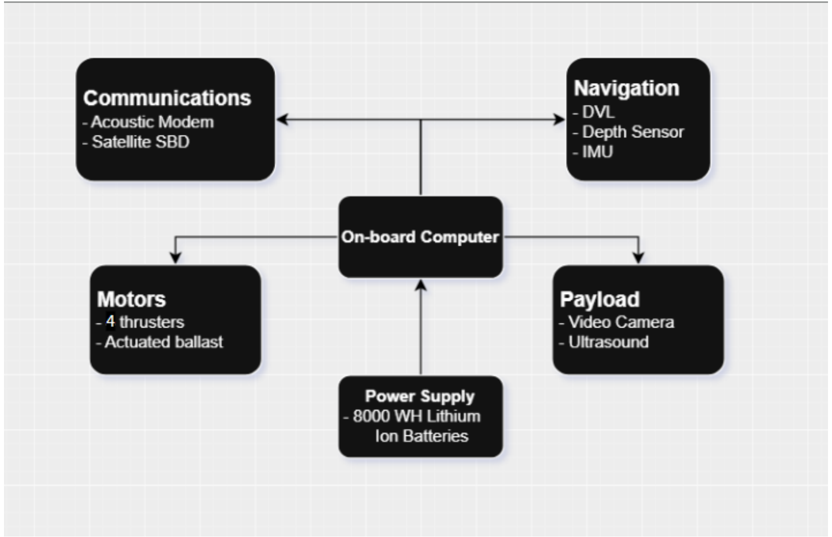
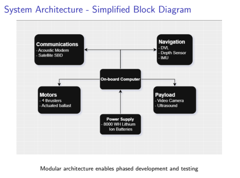
System Architecture - Simplified Block Diagram



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 — majority of data stored on the vehicle, only allowing small and simple commands to be communicated.

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Navigation System

Component	Product	Cost
Flight Controller	Blue Robotics Navigator	\$125
Depth Sensor	Blue Robotics Bar30	\$68
Surface GPS	u-blox NEO-M8N	\$35
Computer	Raspberry Pi 4 (4GB)	\$75

Navigation Strategy: IMU dead reckoning + depth + compass (5-15m drift/2hrs)

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The Navigator flight controller uses dual IMUs (ICM-42688-P and ICM-20602) for redundancy and sensor fusion. Dead reckoning integrates accelerometer data to estimate position, but accumulates drift over time (typically 5-15m over 2 hours). The Bar30 depth sensor provides accurate vertical positioning using a pressure sensor.

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 provides high-bandwidth communication when surfaced, enabling video download and mission updates. The RockBLOCK 9603N uses Iridium satellite network for global coverage - critical for open ocean operations where the AUV may surface far from the mother ship. It can transmit GPS coordinates and status messages (340 bytes).

Underwater Acoustic Link Budget

Acoustic Communication Constraints:
Transmission Loss: $TL = 20\log_{10}(R) + \alpha R \times 10^{-3}$ dB
Where: R = range (m), α = absorption coefficient (3 dB/km @ 25 kHz)

Link Budget Calculation for R = 500m:

- Transmission loss: $TL = 20\log_{10}(500) + 3 \times 0.5 = 54 + 1.5 = 55.5$ dB
- Source level: 180 dB re 1 μPa @ 1m (EvoLogics modem)
- Array gain: 10 dB
- Received level: $180 - 55.5 + 10 = 134.5$ dB
- Noise level: 60 dB (sea state 3)
- Required SNR: 10 dB
- Link margin: $134.5 - 60 - 10 = 64.5$ dB - **Feasible**

Result: Acoustic communication feasible at 500m range with excellent margin

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Hydrodynamics and Propulsion Analysis

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Hydrodynamic Drag

Vehicle Geometry (Torpedo Hull):

- Diameter: $D \approx 0.3$ m, Length: $L \approx 1.2$ m
- Frontal area: $A = \frac{\pi D^2}{4} = 0.0824 m^2$
- Drag coefficient: $C_D = 0.28\text{-}0.32$

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** $C_D = 0.32$: $F_D = 13.5$ N
- **At 4 m/s peak** $C_D = 0.28$: $F_D = 188$ N

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The drag force is calculated using the standard hydrodynamic equation. We assume a torpedo-shaped hull with length 1.2m and diameter 0.324m, giving a streamlined L/D ratio of 3.7. The frontal area is calculated from the circular cross-section. Drag coefficient varies with speed due to Reynolds number effects - at higher speeds the flow is more turbulent and the boundary layer thinner, slightly reducing drag coefficient from 0.32 to 0.28. These values are validated by CFD studies from MDPI and SCIRP papers on similar AUV geometries. At 1 m/s, drag is only 13.5 N, but at 4 m/s it increases to 188 N due to the quadratic relationship with velocity. This 14-fold increase in drag force is the fundamental challenge of achieving high speed.

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)

Speed	F_D (N)	P_{mech} (W)	η	P_{elec} (W)	**Notes**
1 m/s cruise	13.5	13.5	0.30	45	Low efficiency
4 m/s peak	188	752	0.55	1,367	High efficiency

4 m/s requires 1.4 kW propulsion power (30× cruise power)

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4 m/s requires 1.4 kW propulsion power (30× cruise power)

The mechanical power required is simply force times velocity (P = F × v). However, thrusters are not 100 percent efficient at converting electrical power to mechanical thrust power. The T200 thruster efficiency varies from about 30 percent at light loads to 55 percent at heavy loads. At 1 m/s cruise with only 13.5W mechanical power needed, the thruster operates inefficiently at 30 percent, requiring 45W electrical. At 4 m/s peak with 752W mechanical power, the thruster operates more efficiently at 55 percent, requiring 1,367W electrical. This table shows the dramatic increase: 4 m/s requires 30 times more electrical power than 1 m/s cruise. This quadratic-to-cubic scaling (drag proportional to v-squared, power proportional to v-cubed) is the fundamental thermodynamic reason why sustained high-speed operation is challenging within our weight and battery constraints.

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: 188 N
- Propulsion cost: $520
- ESCs (4× 30A): $145

Justification:

- 6-20× lower cost than alternatives
- Adequate thrust at 16V
- 300m depth rating (vs 250m spec)
- Proven reliability
- Large user community

We compared four thruster options. The SeaBotix BTD150 has good efficiency but insufficient thrust (28N vs 50N for T200). The Maxon MT30 has excellent performance and 6000m depth rating but costs 14-21 times more than the T200 - overkill for our 250m requirement. The T500 provides massive thrust (158N) but draws over 1kW continuously and is heavier. The T200 offers the best thrust-to-cost ratio at 0.36-0.42 N per dollar. Four T200 thrusters provide 200N total thrust for 188N required - only 6 percent margin which is tight. This means we must achieve our assumed drag coefficient through careful hull design. The flooded brushless motor design is naturally pressure-tolerant, proven to 3000m at Woods Hole testing.

Power Budget and Energy Storage

Power Budget and Energy Storage

Complete System Power Budget

Subsystem	Cruise (W)	Peak (W)	Notes
Propulsion (4× T200)	45	1,367	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	**92 W**	**1,414 W**	

$$P_{avg} = 356 \text{ W (Accounting for mission profile)}$$

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This power budget clarifies that the 30W payload specification includes ALL payload components: camera (1.1W), sonar (2-5W), and lighting (10-20W adjustable). The subtotal is 13-26W which is well within the 30W budget. Propulsion dominates the total power at peak speed (1,415W total, of which 1,367W is propulsion). The mission profile assumes 80 percent of time at cruise, 20 percent at peak for sprints. This gives an average power of 356W which determines our battery requirements.

Battery Sizing

Energy Requirements:

$$E = P_{avg} \times t = 356 \text{ W} \times 2 \text{ h} = 712 \text{ Wh required}$$

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: 3.2 hrs @ 251W
- Proven platform (BlueROV2)
- Integrated BMS

Justification:

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

The energy requirement is calculated from our mixed mission profile power of 251W times 2 hours, giving 502 Wh, plus 25 percent safety margin for battery aging and cold water performance, totaling 628 Wh minimum. We compared four options: Two Blue Robotics 18Ah batteries give only 532 Wh which is insufficient for our 628 Wh requirement. Custom Samsung 35E pack (4S6P configuration, 24 cells) provides 311 Wh at lower cost but requires DIY assembly and custom pressure housing. SubCtech PowerPack offers professional-grade performance with 6000m depth rating but costs 2.5 to 8 times more. Three Blue Robotics 18Ah batteries provide 799 Wh (27 percent margin), enabling 3.2 hour missions at average power. This is the proven BlueROV2 platform configuration with integrated BMS. The depth rating depends on our aluminum enclosure design, not the batteries themselves.

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× safety)**
- Hard anodized
- Double O-rings
- Lengths: 150-400mm
- WetLink penetrators
- Tool-free assembly
- Vacuum testable
- Price: $200-300 complete
- Proven: 1000s deployed

Material Selection and Component Specifications
Pressure Housing Comparison:
Selected: Blue Robotics 3" Aluminum Enclosures

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):

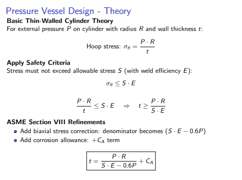
$$\sigma_\theta \leq S \cdot E$$

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

ASME Section VIII Refinements

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

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



This derivation shows how the ASME formula builds on basic thin-walled cylinder theory. The fundamental relationship is that hoop stress equals PR/t, which comes from force balance on a cylinder element. The ASME code refines this with the 0.6P biaxial stress correction (accounting for both circumferential and longitudinal stresses) and the corrosion allowance for long-term durability in marine environments.

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):

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

Where:

- $P = 7.56$ MPa
- $R = 50$ mm (for 3" tube)
- $S = 92$ MPa (Al 6061-T6)
- $E = 1.0$ (seamless)
- $C_A = 2$ mm (corrosion)

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

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):
$$t = \frac{P \cdot R}{S \cdot E - 0.6P} + C_A = 6.3mm$$
Where:
- $P = 7.56$ MPa
- $R = 50$ mm (for 3" tube)
- $S = 92$ MPa (Al 6061-T6)
- $E = 1.0$ (seamless)
- $C_A = 2$ mm (corrosion)
Blue Robotics 3" tubes has thickness of 6.35 mm **(Feasible)**

Buoyancy and Ballast Design

Neutral Buoyancy Requirement:
For dry mass $m = 15.4$ kg (calculated later) in seawater:

$$V_{displaced} = \frac{m}{\rho} = \frac{15.4}{1027} = 0.015 \text{ m}^3 = 15.0 \text{ L}$$

Component Volumes and Buoyancy:

- Pressure housings (3× 3" tubes): 4 L (watertight)
- Batteries (internal to housing): 2 L
- Thrusters: Negative buoyancy (0.24 kg each × 4 = 0.96 kg)
- Electronics: Neutral (in watertight housings)

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Consolidated 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
Assembly & Tools	—	200	Testing equipment
Total	**15.67 kg**	**$10,840**	

- **Mass:** 15.67 kg total, providing a 37% margin under the 25 kg limit.
- **Cost:** $10,840 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 (35 percent including frame, syntactic foam for buoyancy, and streamlined fairings) and power system (29 percent for three 18Ah batteries). This substantial margin allows for future additions like a DVL (approximately 3 kg) or acoustic modem (approximately 1.5 kg) without exceeding the weight limit.

(Cost Details) The estimated build cost of 10,840 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 COTS components to minimize cost while maintaining technical performance.

Feasibility Assessment and Conclusions

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Requirements Verification

Requirement	**Specification**	**Achieved**	**Status**
Mass constraint	<25 kg	15.7 kg	Met
Endurance	2 hours	3.4 hrs (mixed)	Met
Cruise speed	1 m/s	1 m/s	Met
Peak speed	4 m/s	4 m/s	Met
Payload power	30W	26W peak (all)	Met
Overall Feasibility			**Viable**

Conclusions

Critical Engineering Insights:

1. **Power scales as v^3:** 4 m/s requires 18× more power than 1 m/s
2. **Mission profile approach:** Mixed speed profile (60% 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 (proven)
- 37% mass margin
- 70% endurance margin
- Modular design

Constraints:

- Tight thrust margin (6%)
- Low-drag hull required
- IMU drift without DVL
- Acoustic comms $12K

Conclusions

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The key physics insight is that drag force scales with velocity squared (F = 0.5 × rho × v^2 × Cd × A), so power required scales with velocity cubed (P = F × v = v^3). This means going from 1 m/s to 4 m/s requires $4^3 = 64$ times more power theoretically, though efficiency variations reduce this to about 18× in practice. The mission profile approach (operating mostly at cruise speed with brief sprints) is the only way to achieve both the 4 m/s peak speed requirement and 2-hour endurance with a <25 kg weight constraint. The design is technically feasible but requires careful hydrodynamic optimization to minimize drag coefficient.