

Free-Roving Subsea Cable Inspection Drone

A Technical Feasibility Study

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November 11, 2025

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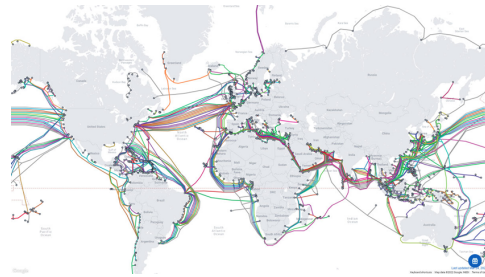
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Problem - Subsea Cable Inspection

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)



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Free-Roving Subsea Cable Inspection Drone

└ Problem - Subsea Cable Inspection

└ Problem - Why Subsea Cables Matter

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 - Why Subsea Cables Matter

- Backbone of the Internet:
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 - 500+ cables worldwide
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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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└ Problem - Subsea Cable Inspection

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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

Requirements and Operating Environment

“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: $P = \rho gh \approx 25 \text{ bar}$
- Temperature: 4°C seawater
- No GPS/RF underwater
- Saltwater corrosion
- Turbid water (limited visibility)

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At 250 m depth, the pressure is approximately 25 bar (2.5 MPa). This is calculated using $P = \rho g h$, where ρ 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.

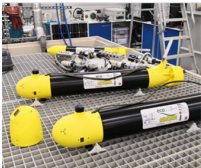
Existing Commercial Solutions

Existing Commercial Solutions

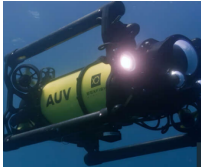
Model	Type	Mass	Depth	Speed	Endurance	Cost
Our Target	AUV	<25 kg	250m	4 m/s peak	2 hrs	\$10-23K
Iver3 (L3Harris)	AUV	27-39 kg	100m	1.3 m/s	8-14 hrs	\$75-120K
ecoSUB m-Power+	AUV	17 kg	500m	1.5 m/s	8-10 hrs	£35-50K
Boxfish AUV	AUV	25 kg	300-600m	2 m/s	10 hrs	\$80-150K
BlueROV2	ROV	10-11 kg	100-300m	1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

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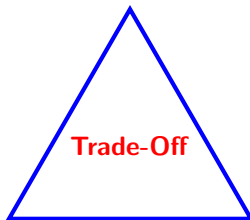
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Many commercial solutions exist but vary in capability. Commercial designs such as the Iver3 and ecoSUB use fully autonomous operation with single thruster plus fins for pitch/yaw control. The Boxfish uses 8 vectored thrusters for full 6-DOF control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

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 m/s) + 20% sprint (4 m/s)*

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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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Design Approach and System Architecture

System Design Directions

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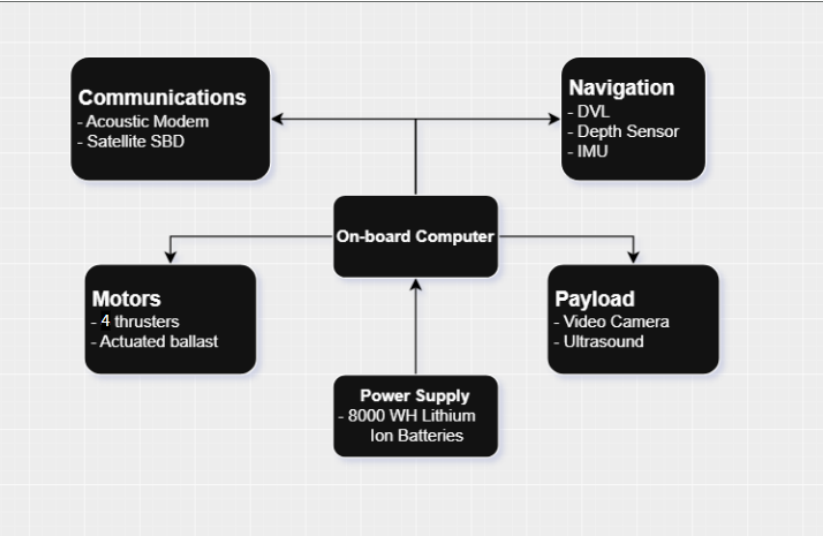
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The design uses an autonomous approach instead of tethered ROV operation. Tethered ROVs require continuous high-bandwidth communication for real-time control, which is only possible with a physical cable limiting range and adding complexity. Autonomous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



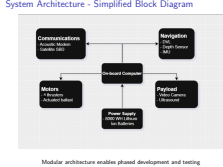
Modular architecture enables phased development and testing

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Design Approach and System Architecture

System Architecture - Simplified Block Diagram



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

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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Radio frequency signals attenuate extremely rapidly in seawater due to conductivity. Skin depth at WiFi frequencies is less than 10 centimeters. Effective RF range underwater is only a few meters maximum, making it useless for cable inspection missions.

Optical communication uses laser or LED light transmission. Water absorbs and scatters light, with attenuation increasing significantly in turbid or murky conditions. Optical systems require direct line-of-sight and operate at ranges under 100 meters in clear water, much shorter in realistic ocean environments with sediment and particulates.

Acoustic communication is the only viable long-range option. Sound propagates well in water with ranges exceeding several kilometers. However, acoustic modems have severe limitations: data rates around 1 to 10 kilobits per second, latency of seconds due to slow sound speed, and interference from reflections off the surface and seafloor. Cost is also prohibitive - acoustic modems cost 12,000 dollars versus 310 dollars for WiFi plus Iridium satellite.

The design solution stores most sensor data onboard during the mission. High-resolution camera video and sonar scans are recorded to the Raspberry Pi storage. At the surface, WiFi provides high-bandwidth data transfer at 50 megabits per

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 is the core stabilization board. Its dual IMUs are fused by the software to reduce sensor noise and drift.

The Raspberry Pi 4 is the "brain" or main computer. It runs the high-level autopilot software and processes all the mission and sensor data.

The Bar30 sensor just measures water pressure, which gives us a very accurate vertical position (depth).

For horizontal position, GPS only works on the surface. The Surface GPS is used to get a precise starting point before the drone dives. Once underwater, the drone uses IMU dead reckoning—it estimates its position by tracking its own movement from that GPS starting point. This estimation is imperfect and accumulates errors, which causes the 5-15m drift over the mission.

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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Communications and Navigation

Communications Systems

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At the surface, WiFi provides 150 megabits per second bandwidth for downloading video and sensor data. The vehicle also acquires GPS fixes to reset navigation drift.

For open ocean operations beyond visual range, the RockBLOCK uses the Iridium satellite network with global coverage. Every 10 minutes, the vehicle surfaces and transmits 340-byte messages containing GPS coordinates and status. This ensures vehicle recovery even kilometers from the mothership.

The autonomous mission profile eliminates the need for real-time underwater communication. The vehicle follows pre-programmed waypoints, stores all sensor data onboard, and downloads it during surface intervals.

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 μ Pa @ 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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- └ Communications and Navigation
 - └ Underwater Acoustic Link Budget

This link budget calculation demonstrates that underwater acoustic communication is technically feasible

Transmission loss has two components: spreading loss at $20 \log R$ from geometric spreading, and absorption loss α times R . At 25 kilohertz, seawater absorption is approximately 3 decibels per kilometer, giving 1.5 decibels absorption at 500 meters.

The calculation: EvoLogics modem source level is 180 decibels re 1 micropascal at 1 meter. After 500 meters, transmission loss is 55.5 decibels. Array gain adds 10 decibels. Received signal level is 134.5 decibels.

Ocean ambient noise at sea state 3 is 60 decibels. Required signal-to-noise ratio for reliable communication is 10 decibels, meaning minimum received level of 70 decibels. The link margin is 64.5 decibels, sufficient to handle multipath interference and unexpected losses.

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Hydrodynamics and Propulsion Analysis

Hydrodynamic Drag

Vehicle Geometry (Torpedo Hull):

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

Drag Force Equation:

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

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

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

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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

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Hydrodynamics and Propulsion Analysis

Thruster Selection - T200

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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 x T200 Configuration:

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

Justification:

- 5-20x lower cost than alternatives
- Adequate thrust
- 300m depth rating (vs 250m spec)
- Proven reliability

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- 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

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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- Free-Roving Subsea Cable Inspection Drone
 - Power Budget and Energy Storage
 - Complete System Power Budget

Complete System Power Budget

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TOTAL	86 W	1,225 W	

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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. At cruise, propulsion is only 39 watts out of 86 watts total. The mission profile assumes 80 percent time at 1 meter per second cruise, 20 percent at 4 meters per second sprint. This gives 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)
- Integrated BMS

Justification:

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

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Free-Roving Subsea Cable Inspection Drone

Power Budget and Energy Storage

Battery Sizing

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Energy requirement is 314 watts times 2 hours 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 in 4S6P configuration with 24 cells provides 311 watt-hours at lower cost, but requires 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 BlueROV2 platform with integrated battery management system.

Battery depth rating depends on the aluminum pressure enclosure design, not the battery cells themselves.

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/m ³	\$7	Excellent
Ti Grade 5	880	4,430 kg/m ³	\$30	Overkill (6000m+)
Acrylic	70-75	1,180 kg/m ³	\$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

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Free-Roving Subsea Cable Inspection Drone

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Three materials were compared for pressure housing. Aluminum 6061-T6 has yield strength of 276 megapascals and density of 2,700 kilograms per cubic meter. Titanium Grade 5 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. Double O-ring seals ensure water-tight integrity. Available lengths from 150 to 400 millimeters enable modular layout.

WetLink penetrators provide cable entry at 12 to 17 dollars per unit, rated to 1000 meters. These are tool-free, reusable, and significantly cheaper than traditional potted penetrators. Complete enclosures cost 200 to 300 dollars. Thousands deployed in BlueROV2 fleet validate reliability.

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

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

Free-Roving Subsea Cable Inspection Drone

└ Mechanical Design and Structural Analysis

└ Pressure Vessel Design - Theory

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 for pressure vessel design under external pressure.

Pressure Vessel Design - Theory

Basic Thin-Walled Cylinder Theory

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

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Pressure Vessel Design - ASME Calculation

Operating Conditions:

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

ASME Section VIII Formula (External Pressure):

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

Where:

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

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

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Mechanical Design and Structural Analysis

Pressure Vessel Design - ASME Calculation

Operating pressure at 250 meters is ρgh equals 2.52 megapascals or 25.2 bar. With safety factor of 3, design pressure is 7.56 megapascals.

Applying ASME Section VIII formula: P is 7.56 megapascals, R is 50 millimeters for 3 inch tube internal radius. Allowable stress S for aluminum 6061-T6 is yield strength divided by 3, giving 92 megapascals. Weld efficiency E is 1.0 for seamless tube. Corrosion allowance C-A is 2 millimeters for marine environment. Calculation gives t equals 7.56 times 50, over 92 times 1.0 minus 0.6 times 7.56, plus 2. This equals 378 divided by 87.5, plus 2, giving 4.3 plus 2 equals 6.3 millimeters minimum thickness.

Blue Robotics 3 inch tubes have 6.35 millimeter wall thickness - essentially identical to calculated requirement. This validates the pressure housing design for 250 meter operation with appropriate safety margins.

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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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Free-Roving Subsea Cable Inspection Drone

- └ Mechanical Design and Structural Analysis
- └ Buoyancy and Ballast Design

Buoyancy and Ballast Design

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- ▲ Electronics: Neutral (in watertight housings)

Neutral buoyancy requires displaced volume equal to mass divided by seawater density. For dry mass of 15.4 kilograms, required displaced volume is 15.4 divided by 1027, equals 0.015 cubic meters or 15 liters.

Component contributions: Three 3 inch aluminum tubes displace approximately 4 liters as watertight volumes. Batteries inside housings occupy approximately 2 liters. Electronics in watertight housings are approximately neutral buoyancy.

Thrusters have negative buoyancy: each T200 is 0.24 kilograms negative in water, giving 0.96 kilograms total for four thrusters. This must be compensated with syntactic foam providing positive buoyancy.

Final buoyancy adjustment uses lead weights for fine trim, positioning center of gravity below center of buoyancy to ensure passive stability in roll and pitch.

Consolidated Mass and Cost Budgets

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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Free-Roving Subsea Cable Inspection Drone

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Assembly & Tools	—	200	Testing equipment
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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

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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Free-Roving Subsea Cable Inspection Drone

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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 key enabler is the mission profile approach: 80 percent time at 1 meter per second cruise, 20 percent at 4 meters per second sprint. Sustained 4 meters per second operation would require 2,450 watt-hours for 2 hours, exceeding weight constraints. The mixed profile reduces average power to 314 watts, making the design feasible.

Conclusions

Critical Engineering Insights:

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

Strengths:

- COTS components (proven)
- 37% mass margin
- 25% endurance margin
- Modular design

Constraints:

- 23% thrust margin
- Low-drag hull required
- IMU drift without DVL
- Acoustic comms \$12K

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Free-Roving Subsea Cable Inspection Drone

Feasibility Assessment and Conclusions

Conclusions

The fundamental physics 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. Sustained high speed is thermodynamically incompatible with the weight constraint.

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. T200 thrusters provide 0.38 newtons per dollar thrust-to-cost ratio, 6 to 20 times better than alternatives. COTS components from Blue Robotics ecosystem reduce integration risk and cost.

The design is technically feasible with 23 percent thrust margin, 37 percent mass margin, and 25 percent endurance margin. Main constraint is the tight thrust

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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/\$
- 6-20× cheaper than alternatives

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Free-Roving Subsea Cable Inspection Drone

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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
- $3\times = 799$ Wh total
- Mass: 1.35 kg each
- Cost: \$400 each

3" AI Enclosure:

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

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Free-Roving Subsea Cable Inspection Drone

└ Navigator & Bar30

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Sources: bluerobotics.com

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

Sources: bluerobotics.com; sparkfun.com

RockBLOCK 9603N:

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

GPS position reporting

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Free-Roving Subsea Cable Inspection Drone

└ Ping360 & RockBLOCK

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References

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- T200 Thruster: <https://bluerobotics.com/store/thrusters/t200-thruster-r2-rp/>
- 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>

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- 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

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