Free-Roving Subsea Cable Inspection Drone

A Technical Feasibility Study

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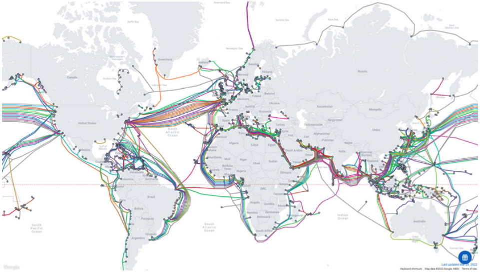
Problem - Subsea Cable Inspection

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)



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

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

Problem Definition

Hydrodynamics
Analyze underwater drag forces to estimate thrust needed for efficient movement.

- Degrees of freedom and stability control
- Drag and resistive forces

Power Consumption
Identify energy storage limits to define mission duration and vehicle size within constraints.

- 2 hours continuous operation
- Support 30W load as well as communications and mechanical systems

Mechanical Design
Develop the mechanical system ensuring all components fit within the 25kg weight limit.

- Buoyancy system
- Structural integrity

Communication and Control
Assess feasibility of underwater wireless communication methods for control and data transfer.

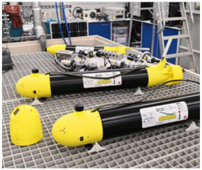
- Attenuation in seawater
- Navigation and mapping

Existing Commercial Solutions

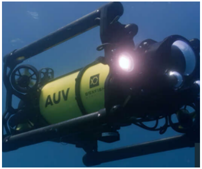
Existing Commercial Solutions

Model	Type	Mass	Depth	Speed	Endurance	Cost
Our Target	AUV	<25 kg	250m	4 m/s peak	2 hrs	$9-10K
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

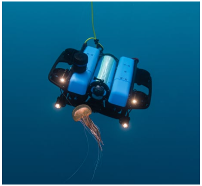
Iver3: Single thruster + fins



ecoSUB: 500m rated, alkaline



Boxfish: Tethered AUV, 6-DOF



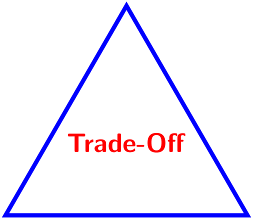
BlueROV2: Tethered ROV, 6-DOF

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

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)

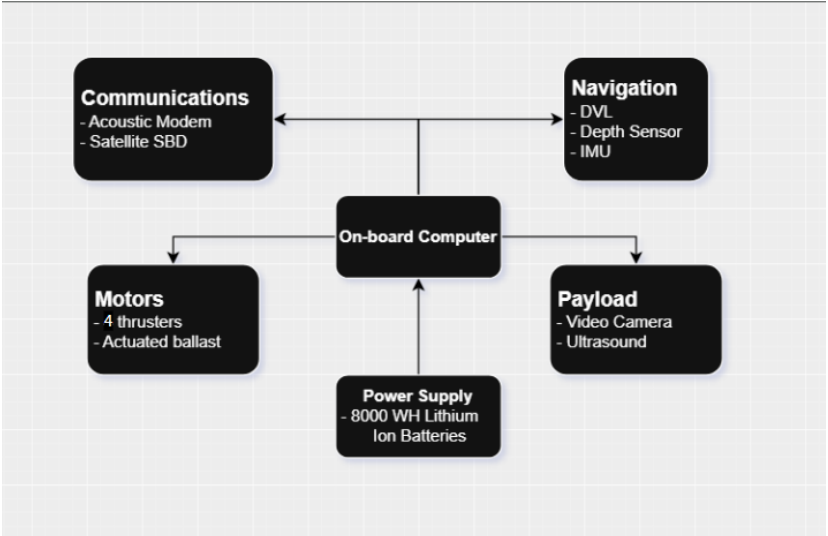
Mass $<$ 25kg limits battery size and therefore power supply (limits endurance), also sacrifices equipment or payload (decreased capabilities)

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

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
- 4-thruster design gives a good balance between maneuverability, stability, and power efficiency
  - Sufficient for precise hovering 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

System Architecture - Simplified Block Diagram



Modular architecture enables phased development and testing

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

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

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.

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	\$220 \$300
Depth Sensor	Bar30 (MS5837) Keller PA-7LD	2mm resolution, ±2m accuracy ±0.3m accuracy, stable	\$90 \$200-500
Surface GPS	u-blox NEO-M8N RTK GPS	2.5m accuracy <0.1m accuracy	\$35 \$300-600
Computer	Raspberry Pi 4	Quad-core ARM, 4GB RAM	\$75
DVL (Optional)	Nortek DVL1000 Teledyne Pathfinder	0.2 cm/s, ¡1m over 2 hrs Similar, proven	\$20,000 \$18-28K

Baseline Cost: \$420 (Navigator + Bar30 + u-blox + RPi4)

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

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)

Thruster Selection - T200

Model	Thrust (N)	Power (W)	Depth (m)	Mass (kg)	Cost ($)	Thrust/Cost
T200	**51.5 fwd**	**390 max**	**300**	**0.427**	**230**	**0.22**
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: **206 N**
- Required: 162 N
- Propulsion cost: $920
- ESCs (4× 30A): $160

Justification:

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

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**	

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

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**	**803 Wh**	**4.05 kg**	**$1,275**
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: 803 Wh
- Endurance: 2.6 hrs @ 314W
- Proven platform (BlueROV2)

Justification:

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

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
- Lengths: 150-400mm

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

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

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)**

Mass and Cost Budgets

Mass & Cost Summary

Subsystem	Mass (kg)	Cost ($)	Key Components
Propulsion	1.88	1,080	4× T200 + ESCs
Power	4.55	1,755	3× 18Ah batteries + housing
Control & Navigation	0.62	765	RPi4 + Navigator + Bar30 + GPS
Payload	0.96	3,370	Ping360 ($2,750) + camera + light
Communications	0.12	310	WiFi + Iridium
Structure	5.50	1,917	Frame, foam, fairings, penetrators
Total	**15.67 kg**	**$9,197**	

- **Mass:** 15.67 kg total, providing a 37% margin under the 25 kg limit.
- **Cost:** $9,197 total build cost
- **Key Drivers:** Power/Structure are largest mass contributors; Payload (Ping360) is the largest cost.

Conclusions

Requirements Verification

Requirement	**Specification**	**Achieved**	**Status**
Mass constraint	<25 kg	15.7 kg	Met
Endurance	2 hours	2.6 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**

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 (0.22 N/$)

Strengths:

- COTS components
- 37% mass margin
- 28% endurance margin
- Modular design

Constraints:

- Low-drag hull required
- IMU drift without DVL

Appendix: Datasheets

Selected Component Specifications

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

T200 Thruster

- Thrust: 51.5 N fwd @ 16V
- Max power: 390W
- Efficiency: 30% @ light load, 55% @ heavy load
- Depth rating: 300m
- Mass: 427g air, 239g in water
- Cost: $230

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

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: $220

Bar30 Depth Sensor:

- Range: 0-300m
- Resolution: 2mm
- Cost: $90

18Ah Li-ion Battery:

- Voltage: 14.8V (4S)
- Capacity: 267.6 Wh each
- $3\times = 803$ Wh total
- Mass: 1.35 kg each
- Cost: $425 each

3" Al Enclosure:

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

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

References

Selected Components (Blue Robotics):

- 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

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