

# Free-Roving Subsea Cable Inspection Drone

## A Technical Feasibility Study

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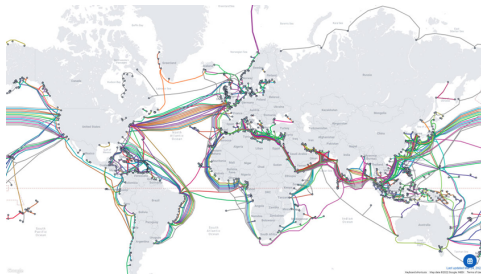
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## Problem - Subsea Cable Inspection

# 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)



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

# Problem Definition

## Communications and Navigation

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

- Attenuation in seawater
- Navigation and mapping

## Power Budget Analysis

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

## Hydrodynamics

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

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

## Mechanical and Structural Design

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

- Buoyancy system
- Structural integrity

# Existing Commercial Solutions



# Existing Commercial Solutions

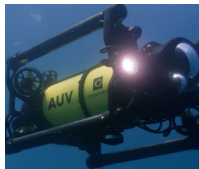
Model	Type	Mass	Depth	Speed	Endurance	Cost
<b>Our Target</b>	AUV	<25 kg	250m	4 m/s peak	2 hrs	\$9-10K
Iver3 (L3Harris)	AUV	27-39 kg	100m	1.3 m/s	8-14 hrs	\$75-120K
ecoSUB m-Power+	AUV	17 kg	500m	1.5 m/s	8-10 hrs	£35-50K
Boxfish AUV	AUV	25 kg	300-600m	2 m/s	10 hrs	\$80-150K
BlueROV2	ROV	10-11 kg	100-300m	1 m/s	3-5 hrs	\$3-3.5K



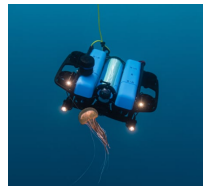
Iver3: Single thruster + fins



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)

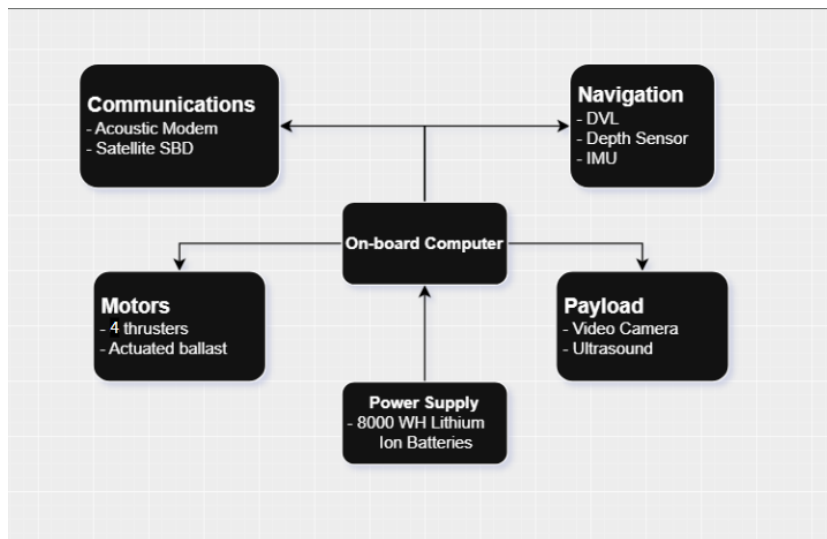
**Mass** < 25kg limits battery size and therefore power supply (limits endurance), also sacrifices equipment or payload (decreased capabilities)

**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)	$2.8^\circ/\text{s}/\sqrt{\text{Hz}}$ gyro noise	\$220
	Pixhawk 6C	Similar performance	\$300
Depth Sensor	Bar30 (MS5837)	2mm resolution, $\pm 2\text{m}$ accuracy	\$90
	Keller PA-7LD	$\pm 0.3\text{m}$ accuracy, stable	\$200-500
Surface GPS	u-blox NEO-M8N	2.5m accuracy	\$35
	RTK GPS	$< 0.1\text{m}$ accuracy	\$300-600
Computer	Raspberry Pi 4	Quad-core ARM, 4GB RAM	\$75
DVL (Optional)	Nortek DVL1000	0.2 cm/s, $\pm 1\text{m}$ over 2 hrs	\$20,000
	Teledyne Pathfinder	Similar, proven	\$18-28K

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

# Hydrodynamics 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<sup>2</sup>
- 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  $\rho = 1027$  kg/m<sup>3</sup> (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<sup>[T200]</sup>)

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

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

# Thruster Selection

Model	Thrust (N)	Power (W)	Depth (m)	Mass (kg)	Cost (\$)	Thrust/Cost
<b>T200</b>	<b>51.5 fwd</b>	<b>390 max</b>	<b>300</b>	<b>0.427</b>	<b>230</b>	<b>0.22</b>
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 Analysis

# 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
<b>TOTAL</b>	<b>86 W</b>	<b>1,225 W</b>	

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



# 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
<b>Blue Robotics 3×18Ah</b>	<b>14.8V</b>	<b>18Ah</b>	<b>803 Wh</b>	<b>4.05 kg</b>	<b>\$1,275</b>
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 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 <sup>3</sup>	\$7	Excellent
Ti Grade 5	880	4,430 kg/m <sup>3</sup>	\$30	Overkill (6000m+)
Acrylic	70	1,180 kg/m <sup>3</sup>	\$4	Insufficient

## Selected: Blue Robotics 3" Aluminum Enclosures

- ID: 74.7mm, Thickness: 6.35mm
- Depth: 500m (2× safety)
- Hard anodized

# 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  $E$ ):

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

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

## ASME Section VIII Refinements<sup>[ASME]</sup>

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

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

# 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):<sup>[ASME]</sup>

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

Where:

- $P = 7.56 \text{ MPa}$
- $R = 50 \text{ mm}$  (for 3" tube)
- $S = 92 \text{ MPa}$  (Al 6061-T6:  $\sigma_{yield}$ /safety factor of 3 =  $276/3$ )
- $E = 1.0$  (seamless)
- $C_A = 2 \text{ mm}$  (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
<b>Total</b>	<b>15.67 kg</b>	<b>\$9,197</b>	

- **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
<b>Overall Feasibility</b>			<b>Viable</b>

# 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/](http://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

Sources: [bluerobotics.com](http://bluerobotics.com)

## **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

# 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](http://bluerobotics.com); [sparkfun.com](http://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](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](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>