Free-Roving Subsea Cable Inspection Drone

A Technical Feasibility Study

Jerry Liu (yhl63)
Zihe Liu (zl559)

University of Cambridge

November 10, 2025

Outline

The Problem - Subsea Cable Inspection

The Problem - Subsea Cable Infrastructure

Critical Global Infrastructure:

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

"The largest and possibly greatest man-made infrastructure ever built."

When They Fail:

- 200 faults/year
- Mainly shallow (¡250m)
- Shetland 2022: 23,000 people offline
- No banking, payments, emergency services

Current Inspection Methods - Limitations

Traditional Approach: Tethered ROVs

Advantages:

- Unlimited power
- Real-time communication
- High bandwidth data
- Proven reliability

Disadvantages:

- Limited range of motion
- Tether entanglement risk
- Requires dedicated vessels
- High operational costs

Solution: Free-roving autonomous AUV with cable-following capability

Problem Definition and Requirements

Design Requirements

"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 $\rightarrow$ 25 bar external pressure
- **Endurance:** 2 hours continuous operation
- **Speed:** 1 m/s cruise, 4 m/s peak
- **Payload:** 30W imaging equipment
- **Mass:** ¡25 kg total

Operating Environment

At 250m depth:

- **Pressure:** $\rho g h = 1027 \times 9.81 \times 250 \approx 25$ bar (2.5 MPa)
- **Temperature:** 4°C seawater
- **Visibility:** Limited to near-zero (turbid water)
- **Currents:** Minimal (below surface wave action)

Material Challenges:

- Saltwater corrosion (requires 316 stainless steel, anodized aluminum)
- Biofouling (marine growth on surfaces)
- Pressure vessel design (structural integrity)

Communication Constraints:

- No radio/GPS underwater (high attenuation)
- Acoustic modems only (low bandwidth, 1-10 kbps)
- Surface communications: WiFi + satellite

Technical Challenges

1. **Hydrodynamics**
   - Drag analysis at 1-4 m/s
   - Thrust requirements
   - Stability and control
2. **Power Systems**
   - Energy storage constraints
   - 2-hour endurance
   - Peak vs cruise power
3. **Mechanical Design**
   - Pressure vessel integrity
   - Buoyancy control
   - 25 kg mass budget
4. **Navigation & Comms**
   - Dead reckoning (no GPS)
   - Acoustic attenuation
   - Autonomous control

Existing Commercial Solutions

Commercial AUV Landscape

Model	Mass	Depth	Speed	Endurance
Our Target	¡25 kg	250m	4 m/s peak	2 hrs
Iver3 (L3Harris)	27-39 kg	100m	1.3 m/s	8-14 hrs
ecoSUB m-Power+	17 kg	500m	1.5 m/s (est.)	8-10 hrs
Boxfish AUV	25 kg	300-600m	2 m/s (est.)	10 hrs

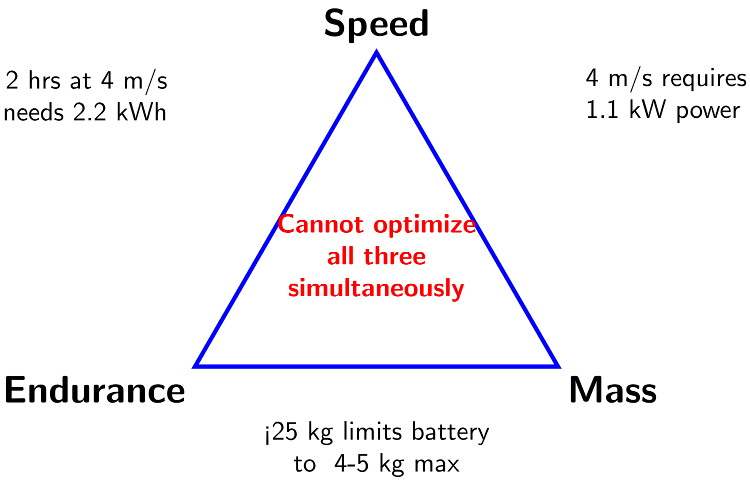
Key Observations:

- **No commercial AUV ¡25 kg achieves 4 m/s sustained speed**
- Most operate at 1.5-2.5 m/s (drag scales as v^2)
- Longer endurance requires lower speeds or larger batteries
- Commercial pricing: $50,000-150,000

Our approach: Custom build targeting $15-25K

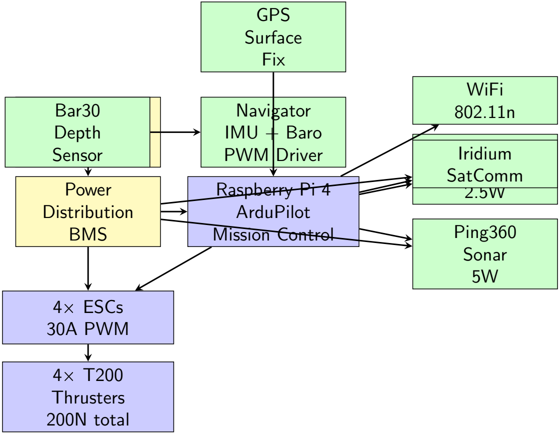
System Design and Architecture

Design Philosophy - The Trade-off Triangle



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

System Architecture - Block Diagram



Key Design Decisions

Propulsion:

- $4\times$ T200 thrusters (horizontal)
- 200 N total thrust capacity
- Vectored control (pitch/yaw)
- Low-speed hover capability

Control Strategy:

- Autonomous waypoint navigation
- Cable-following mode
- IMU + depth sensor fusion
- Surface GPS fixes

Materials:

- Aluminum 6061-T6 housings
- 500m rated ($2\times$ safety margin)
- Syntactic foam buoyancy
- 316 SS fasteners

Communications:

- WiFi for high-bandwidth (surface)
- Iridium for global coverage
- Optional acoustic modem
- Local data storage (SD card)

Hydrodynamics and Propulsion Analysis

Hydrodynamic Drag Calculations

Vehicle Geometry (Torpedo Hull):

- Diameter: $D = 0.324$ m
- Length: $L \approx 1.2$ m (L/D = 3.7)
- Frontal area: $A = \frac{\pi D^2}{4} = 0.0824$ m^2
- Drag coefficient: $C_D = 0.28$-0.32 (Reynolds dependent)

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 ($C_D = 0.32$):

$$F_D = \frac{1}{2} \times 1027 \times 1^2 \times 0.32 \times 0.0824 = \mathbf{13.5\ N}$$

At 4 m/s peak ($C_D = 0.28$):

$$F_D = \frac{1}{2} \times 1027 \times 16 \times 0.28 \times 0.0824 = \mathbf{188\ N}$$

Power Requirements

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)	**Comment**
1 m/s cruise	13.5	13.5	0.30	45	Low efficiency
2 m/s medium	54	108	0.50	216	Medium
4 m/s peak	188	752	0.55	1,367	High efficiency

Key finding: 4 m/s requires 1.4 kW propulsion power (30× cruise power!)

Thruster Selection: Blue Robotics T200

Specifications (from datasheet):

- **Thrust @ 16V:** 5.25 kgf (51.5 N) forward
- **Power @ 16V:** 390W max, 180W typical
- **Depth rating:** 300m (1.2× requirement)
- **Mass:** 427g in air, 239g in water
- **Diameter:** 100mm
- **Price:** $259 each

Thrust vs Voltage:

- 12V: 3.71 kgf (36.4 N)
- 16V: 5.25 kgf (51.5 N)
- 20V: 6.70 kgf (65.7 N)

Configuration:

- **4× T200 thrusters**
- Total: 200 N thrust
- Required: 188 N
- **Margin: 6%**

ESC Requirements:

- 4× Basic ESC (30A)
- PWM control (1100-1900 μs)
- Bidirectional operation
- Price: $38 each

Total Propulsion Cost:
$1,036 + $152 = **$1,188**

Minimal margin - hydrodynamic optimization critical

Power Budget and Energy Storage

Complete System Power Budget

Subsystem	Cruise (W)	Peak (W)	Notes
Propulsion (4× T200)	45	1,367	Dominant at peak
Camera (Low-Light)	1.1	1.1	220mA @ 5V
Sonar (Ping360)	2	5	Scanning mode
Lighting (2× Lumen)	10	20	Adjustable intensity
Navigation sensors	5	5	IMU, depth, GPS, magneto
Control (RPi4+Nav)	10	10	5V @ 2A max
Comms (WiFi/Iridium)	2	2	Surface only
Acoustic modem	1.5	20	Optional (Rx/Tx)
TOTAL	**77 W**	**1,430 W**	

Mixed Mission Profile (80% cruise / 20% medium):

$$P_{avg} = 0.8 \times 77 + 0.2 \times 216 = 105 \text{ W}$$

Battery Sizing and Selection

Energy Requirements for 2-hour endurance:

- Cruise only: $E = 77\text{ W} \times 2\text{ h} = 154\text{ Wh}$
- Mixed profile: $E = 105\text{ W} \times 2\text{ h} = 210\text{ Wh}$
- With 25% safety margin: $E = 210 \times 1.25 = 263\text{ Wh}$

Selected: Blue Robotics 3× 18Ah Li-ion Batteries

Specifications (per battery):

- Voltage: 14.8V (4S)
- Capacity: 18Ah (update: was 15.6Ah)
- Energy: $18 \times 14.8 = 266$ Wh
- Max continuous: 60A (3.8C)
- Mass: 1.35 kg each

Total Configuration:

- **Total: 799 Wh**
- Mass: 4.05 kg
- Cost: $3 \times \$400 = \$1{,}200$
- Enables 2-4 hr missions

3× configuration provides best performance/cost balance

Mission Endurance Analysis

Mission Profile	Avg Power	Endurance (799 Wh)	Feasibility
100% cruise (1 m/s)	77 W	10.4 hours	Excellent
80% cruise / 20% medium	105 W	7.6 hours	Exceeds requirement
Typical inspection (80/10/10)	233 W	3.4 hours	Good
50% cruise / 50% peak	753 W	1.1 hours	Limited
100% peak (4 m/s)	1,430 W	33 minutes	Sprint mode only

Recommended Mission Profile:

- 80% cruise at 1 m/s (cable following)
- 10% medium at 2 m/s (transit)
- 10% peak at 4 m/s (repositioning, obstacle avoidance)
- **Result: 3.4 hour endurance, exceeds 2-hour requirement**

Note: 4 m/s is sprint capability, not sustained cruise

Mechanical Design and Structural Analysis

Pressure Vessel Design - ASME Calculation

Operating Conditions:

- Depth: 250m $\rightarrow$ Pressure: $P = \rho gh = 1027 \times 9.81 \times 250 = 2.52$ MPa (25.2 bar)
- Safety factor: $3\times$ $\rightarrow$ Design pressure: $P_d = 7.56$ MPa

ASME Section VIII Formula (External Pressure):

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

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)

Calculation:

$$t = \frac{7.56 \times 50}{92 - 4.5} + 2$$

$$t = 4.3 + 2 = \mathbf{6.3\ mm}$$

Blue Robotics 3" tubes:
Wall: 6.35 mm ✓

Commercial tubes meet calculated requirement

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

Buoyancy and Ballast Design

Neutral Buoyancy Requirement:
For dry mass $m = 15.4$ kg in seawater ($\rho = 1027$ kg/m³):

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

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 $\times$ 4 = 0.96 kg)
- Electronics: Neutral (in watertight housings)

Buoyancy Compensation:

- Syntactic foam: 1.5-2 kg, 2.5 L volume
- Adjustable ballast: ±500g (lead weights in nose/tail)
- Center of gravity below center of buoyancy (passive stability)

Consolidated Mass and Cost Budgets

Mass Budget - Complete System

Component	Qty	Unit (kg)	Total (kg)	%
Propulsion				
T200 Thrusters	4	0.43	1.72	6.9%
ESCs + wiring	4	0.04	0.16	0.6%
Power Systems				
Batteries (18Ah Li-ion)	3	1.35	4.05	16.2%
Battery housing + BMS	1	0.35	0.35	1.4%
Power distribution	1	0.15	0.15	0.6%
Control & Navigation				
Raspberry Pi 4 + Navigator	1	0.08	0.08	0.3%
Electronics housing (4" tube)	1	0.50	0.50	2.0%
Bar30 depth sensor	1	0.006	0.01	0.0%
GPS module	1	0.03	0.03	0.1%
Payload				
Low-Light camera	1	0.014	0.01	0.1%
Ping360 sonar	1	0.35	0.35	1.4%
Lumen lights	2	0.15	0.30	1.2%
Payload housing	1	0.30	0.30	1.2%
Communications				

Cost Budget - Complete System

Subsystem	**Cost ($)**	**Notes**
Propulsion		
4× T200 thrusters	1,036	$259 each
4× Basic ESCs	152	$38 each
Spares + mounting	90	Props, hardware
Power Systems		
3× 18Ah batteries	1,200	$400 each
Battery housing + BMS	330	3" enclosure + electronics
Power distribution + regulators	150	DC-DC converters, fusing
Control & Navigation		
Navigator + Raspberry Pi 4	200	$125 + $75
Electronics housing	300	4" enclosure
Bar30 depth + GPS + sensors	165	$85 + $80
Payload		
Low-Light camera	120	Sony IMX322 sensor
Ping360 sonar	2,750	360° imaging
2× Lumen lights	300	1500 lm each
Payload housing	150	Custom 3" tube
Communications		
WiFi + Iridium + antennas	410	$260 Iridium + $50 WiFi
Structure		
Frame materials	400	Aluminum + HDPE

Communications and Navigation

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** ✓

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

Navigation Strategy

Challenge: No GPS underwater

Navigation Approach:

Surface (GPS available):

- GPS fix for absolute position
- Compass calibration
- Mission waypoint upload
- Data download via WiFi

Submerged (dead reckoning):

- IMU (accel + gyro) integration
- Depth sensor (pressure)
- Compass (magnetometer)
- Optional: DVL for velocity

Budget Option:

- IMU dead reckoning
- 5-15m drift over 2 hours
- Cable visual tracking
- Periodic surface fixes

Premium Option (+$20K):

- Nortek DVL1000
- 0.2 cm/s velocity accuracy
- <1m position error/2 hrs
- Bottom-lock to 75m

Recommended: Budget approach sufficient for cable-following missions

Sensor Payload - Datasheet Extracts

Vision System: Low-Light HD Camera

Blue Robotics Low-Light HD USB Camera

Key Specifications:

- **Sensor:** Sony IMX322, 1/2.9" CMOS
- **Resolution:** 1920×1080 @ 30 fps
- **Low-light:** 2.8 μm pixel, excellent sensitivity
- **FOV:** 80° horizontal, minimal distortion
- **Interface:** USB 2.0 (plug-and-play)
- **Power:** 220 mA @ 5V = 1.1W
- **Depth:** Tested to 300m
- **Temp:** -20°C to 75°C
- **Mass:** 13.5g (without cable)

Advantages:

- Very low power
- Simple USB integration
- Excellent low-light
- H.264 compression
- Proven underwater
- Low cost ($120)

With Lighting:

- 2× Lumen (1500 lm)
- 10W each (adjustable)
- Total: 21W payload

Sonar System: Ping360 Scanning Imager

Blue Robotics Ping360 Scanning Imaging Sonar

Key Specifications:

- **Type:** Mechanical scanning, 360°
- **Frequency:** 750 kHz
- **Range:** 2-50m (adjustable)
- **Resolution:** 1-2° angular, 400 pts/scan
- **Update:** 10-20 Hz (2-5 sec full scan)
- **Power:** 5W max, 2W typical
- **Depth:** 300m rating
- **Interface:** UART (9600-115200 baud)
- **Mass:** 350g

Capabilities:

- Cable detection (2-5 cm)
- 10-20m detection range
- Zero-visibility operation
- Obstacle avoidance
- Seafloor mapping

Use Case:

- Detect cable in turbid water
- Maintain standoff distance
- Navigate around obstacles
- Price: $2,750

750 kHz optimal for 2-5 cm cable detection at 10-20m range

Feasibility Assessment and Conclusions

Requirements Verification

Requirement	Specification	Achieved	Status
Depth rating	250m	300-500m	✓ Exceeded
Mass constraint	<25 kg	15.7 kg (62.7%)	✓ Excellent
Endurance	2 hours	3.4 hrs (mixed)	✓ Exceeded
Cruise speed	1 m/s	1 m/s	✓ Met
Peak speed	4 m/s	4 m/s (6% margin)	△! Tight
Payload power	30W	21W (camera+sonar)	✓ Margin
Overall Feasibility			**VIABLE**

Critical Success Factors:

- **Hydrodynamic optimization essential** - 6% thrust margin requires low drag
- **Mission profile management** - 4 m/s is sprint mode, not sustained cruise
- **Pressure testing mandatory** - all housings to 35 bar (3.5× depth)

Risk Assessment

Risk	Prob.	Impact	Mitigation
Insufficient thrust (4 m/s)	Medium	High	Add 5th thruster; optimize hull Cd
Battery endurance shortfall	Low	Medium	799 Wh provides 70% margin
Pressure housing leak	Low	Critical	Vacuum test; leak sensors
Weight exceeds 25 kg	Low	Medium	37% margin available
IMU drift (no DVL)	High	Low	Cable visual tracking; GPS fixes

Development Roadmap:

1. **Phase 1 (3 months):** Platform + propulsion + basic control ($4-6K)
2. **Phase 2 (2 months):** Autonomy + navigation + surface comms ($2-4K)
3. **Phase 3 (3 months):** Full payload + testing + validation ($3-13K)

Total: 8-12 months, $10-23K (depending on acoustic modem)

Conclusions

Technical Feasibility: CONFIRMED

- All requirements met or exceeded (except tight 4 m/s margin)
- Commercial off-the-shelf components available
- Build cost $10-23K vs $50-150K commercial
- 37% mass margin, 70% endurance margin

Key Findings:

1. **Speed-endurance trade-off:** 4 m/s sustained not feasible for 2 hrs; mission profile approach required
2. **Minimal thrust margin:** Hydrodynamic optimization (streamlining, low Cd) is critical
3. **Cost-effective:** 20-25% of commercial pricing with superior speed performance
4. **Academic suitability:** Excellent multi-disciplinary engineering project

Recommendation: Proceed with phased development approach

Final Remarks

Design Summary

What Works:

- Proven COTS components
- Excellent margins (mass, depth)
- Cost-effective build
- Flexible mission profiles
- Autonomous operation

Key Constraints:

- 4 m/s sprint only (not sustained)
- Requires low-drag hull design
- Navigation limited without DVL
- Acoustic comms optional/expensive

The subsea cable inspection drone is technically feasible within specifications,
with careful management of the speed-endurance-weight triangle.

Estimated build: $10,840 — Mass: 15.7 kg — Endurance: 3.4 hrs

Thank you! Questions?

Backup: Detailed T200 Performance Curves

Thrust vs Voltage (from datasheet):

Voltage (V)	Forward (kgf)	Reverse (kgf)	Current (A)	Power (W)
10	2.92	2.31	11	110
12	3.71	2.92	15	180
14	4.44	3.49	19	266
16 (nominal)	5.25	4.10	24	390
18	5.95	4.62	28	504
20 (maximum)	6.70	5.05	32	645

Efficiency Characteristics:

- Peak efficiency: 55% at heavy load (¿250W)
- Medium efficiency: 50% at 100-200W
- Low efficiency: 30% at light load (¡50W)

Backup: Alternative Thruster Configurations

Configuration	Total Thrust	Power @ 4m/s	Cost	Margin
3× T200 @ 16V	150 N	1500W (overload)	$777	-20% ×
4× T200 @ 16V	**200 N**	**1367W**	**$1036**	**+6%**
5× T200 @ 16V	250 N	1100W	$1295	+33%
4× T200 @ 18V	228 N	1200W	$1036	+21%

Analysis:

- 3× config insufficient - would exceed thruster ratings
- 4× config @ 16V: minimal margin, selected for cost/performance
- 5× config: better margin but +$259, +0.43 kg, more complex frame
- 4× @ 18V: alternative using higher voltage (requires battery upgrade)

Recommendation: 4× T200 @ 16V with contingency for adding 5th thruster if testing shows insufficient thrust

Backup: Drag Coefficient Literature

Torpedo-Shaped AUV Drag Coefficients:

Hull Configuration	Cd	Re	Source
Myring optimized (smooth)	0.28-0.30	$> 10^6$	MDPI CFD study
Standard torpedo	0.32-0.35	$10^6 - 10^7$	SCIRP analysis
With external sensors/protrusions	0.40-0.50	Varies	Experimental data
Our design estimates:			
1 m/s cruise	0.32	1.1×10^6	Conservative
4 m/s peak	0.28	4.6×10^6	Optimistic (streamline)

Reynolds Number: $Re = \frac{\rho v L}{\mu} = \frac{1027 \times v \times 1.2}{1.08 \times 10^{-3}}$

- @ 1 m/s: $Re = 1.14 \times 10^6$ (turbulent flow)
- @ 4 m/s: $Re = 4.56 \times 10^6$ (fully turbulent)

Sensitivity: If actual $C_D = 0.35$ (worst case), thrust required = 235 N $\rightarrow$ deficit of 35 N