

# Free-Roving Subsea Cable Inspection Drone

## A Technical Feasibility Study

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## The Problem - Subsea Cable Inspection

# The Problem - Subsea Cable Inspection

- Backbone of the modern internet infrastructure, carrying 97-99% of all intercontinental data traffic.
- 500+ cables worldwide, a total of 14 million kilometers
- Around 2-5 cm in diameter,

# The Problem - Subsea Cable Inspection

- Averages 200 faults a year, particularly in shallow waters ( 200m)
- Shetland Islands cutoff in 2022
- Traditional inspection methods use tethered ROVs, which can limit motion and increase cost

# 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

# Problem Definition

*"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  $\leq$  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:**  $\leq$  25 kg total



# Operating Environment

## At 250m depth:

- **Pressure:**  $\rho gh = 1027 \times 9.81 \times 250 \approx 25 \text{ bar (2.5 MPa)}$
- **Temperature:** 4°C seawater
- **Visibility:** Limited to near-zero (turbid water). Not affected by surface wave currents driven by wind
- **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

# 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

Model	Mass	Depth	Speed	Endurance
<b>Our Target</b>	~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

# Existing Solutions

## Iver3 by L3Harris

- Rated at 200m
- 27-40kg depending on configuration
- 8-14-hour endurance by 784 WHr of rechargeable lithium-ion batteries
- Single thruster, fins for pitch/yaw control

## ecoSUB

- Rated at 500m
- 4kg depending on configuration
- 10-hour endurance by alkaline batteries
- Single thruster, fins for pitch/yaw control

## Boxfish AUV

- Rated up to 600m
- 25kg with Salt water ballast
- Up to 10 hours by 600Whr Lithium Polymer batteries
- 8 3D-vectorred thrusters allowing 6 DoF

# Technical Approach

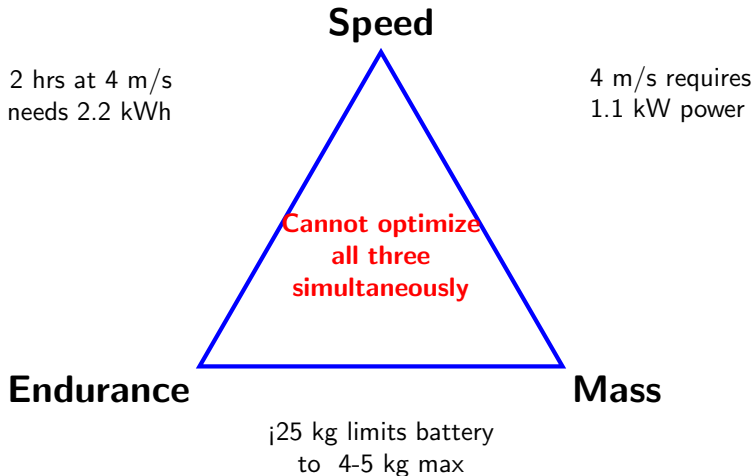
# System Design and Architecture

# System Design

- Autonomous/programmable solution to remove the need for high-quality real-time data transmission which limits untethered ROVs
- 8-thruster design for stability and hovering capabilities for detailed inspection
- Reinforced acrylic casing for

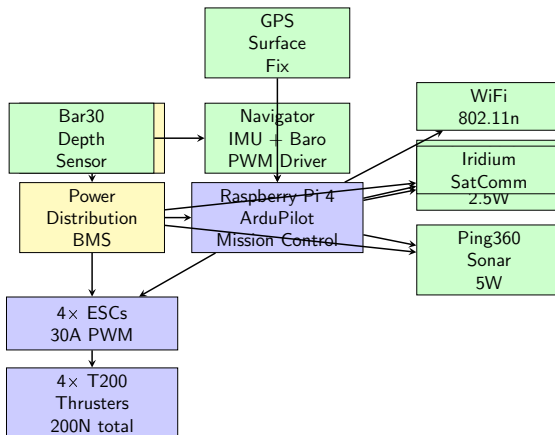


# Design Philosophy - The Trade-off Triangle



**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× 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× 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)

# Communications and Control

# Communications and Control

## Autonomous control with on-board IMU and DVL for real-time navigation and mapping

### Surface:

- RF transmitter: WiFi 802.11n Ethernet standard (possibly needs a base station / emitter on the boat)
- Satellite: Iridium SBD for retrieval and

### Underwater:

- Signal attenuation due to water:
- Received power = Transmitted power - Transmission loss + Array gain
- Transmission Loss (TL) =  $20 \log_{10}(R) + \alpha R \times 10^{-3}$  Where: R = range (m)
- $\alpha$  = absorption coefficient  $\approx 3$  dB/km at 25 kHz
- For R = 500m: TL =  $20 \log_{10}(500) + 3 \times 0.5 = 54 + 1.5 = 55.5$  dB
- Source level: 180 dB re 1  $\mu$ Pa at 1m
- Noise level: 60 dB (sea state 3)
- Array gain: 10 dB
- Required SNR: 10 dB
- Received level =  $180 - 55.5 + 10 = 134.5$  dB
- Margin =  $134.5 - 60 - 10 = 64.5$  dB

# Hydrodynamics

# Hydrodynamics

## Thruster profiling:

- To keep control and power consumption low, we opted for a single thruster design with fins for pitch and yaw control

# Power Consumption



# Mechanical Design

**Ballast design:**

# Cost and Feasibility

# Conclusion

# 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<sup>2</sup>
- 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<sup>3</sup> (seawater)

**At 1 m/s cruise ( $C_D = 0.32$ ):**

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

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

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

# 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)	$\eta$	$P_{elec}$ (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  $\mu$ s)
- 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)
<b>TOTAL</b>	<b>77 W</b>	<b>1,430 W</b>	

**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:  $18 \times 14.8 = 266 \text{ Wh}$
- 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:  $P = \rho gh = 1027 \times 9.81 \times 250 = 2.52 \text{ MPa}$  (25.2 bar)
- Safety factor:  $3\times \rightarrow$  Design pressure:  $P_d = 7.56 \text{ MPa}$

## ASME Section VIII Formula (External Pressure):

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

Where:

Calculation:

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

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

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

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

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

## 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)

## 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)	%
<i>Propulsion</i>				
T200 Thrusters	4	0.43	1.72	6.9%
ESCs + wiring	4	0.04	0.16	0.6%
<i>Power Systems</i>				
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%
<i>Control &amp; Navigation</i>				
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%
<i>Payload</i>				
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%
<i>Communications</i>				

# Cost Budget - Complete System

Subsystem	Cost (\$)	Notes
<b>Propulsion</b>		
4× T200 thrusters	1,036	\$259 each
4× Basic ESCs	152	\$38 each
Spares + mounting	90	Props, hardware
<b>Power Systems</b>		
3× 18Ah batteries	1,200	\$400 each
Battery housing + BMS	330	3" enclosure + electronics
Power distribution + regulators	150	DC-DC converters, fusing
<b>Control &amp; Navigation</b>		
Navigator + Raspberry Pi 4	200	\$125 + \$75
Electronics housing	300	4" enclosure
Bar30 depth + GPS + sensors	165	\$85 + \$80
<b>Payload</b>		
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
<b>Communications</b>		
WiFi + Iridium + antennas	410	\$260 Iridium + \$50 WiFi
<b>Structure</b>		
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),  $\alpha$  = absorption coefficient ( 3 dB/km @ 25 kHz)

## Link Budget Calculation for $R = 500\text{m}$ :

- Transmission loss:  $TL = 20 \log_{10}(500) + 3 \times 0.5 = 54 + 1.5 = 55.5$  dB
- Source level: 180 dB re 1  $\mu\text{Pa}$  @ 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 ✓

**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

### Budget Option:

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

### Submerged (dead reckoning):

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

### 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  $\mu\text{m}$  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			<b>VIABLE</b>

## 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**

## 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 ( $\geq 250\text{W}$ )
- Medium efficiency: 50% at 100-200W
- Low efficiency: 30% at light load ( $\leq 50\text{W}$ )

## Backup: Alternative Thruster Configurations

Configuration	Total Thrust	Power @ 4m/s	Cost	Margin
3× T200 @ 16V	150 N	1500W (overload)	\$777	-20% ×
<b>4× T200 @ 16V</b>	<b>200 N</b>	<b>1367W</b>	<b>\$1036</b>	<b>+6%</b>
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
<i>Our design estimates:</i>			
1 m/s cruise	0.32	$1.1 \times 10^6$	Conservative
4 m/s peak	0.28	$4.6 \times 10^6$	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 → deficit of 35 N