Validation

1 Executive Summary

To support the design of an underwater multi-beacon ranging system, 13 design criteria were established based on customer requirements. Each criterion was quantified through a Technical Performance Measure (TPM), using either requirement values or industry benchmarks. Three communication schemes were evaluated: Option A (sequential single-frequency transmission), Option B (time-synchronous single-frequency), and Option C (simultaneous multi-frequency).

Scores were assigned to each design based on TPM performance, weighted by requirement importance and benchmark improvement. Option C achieved the highest score (0.81) for its efficiency in latency and signal distinction but requires more complex hardware. Option A, currently implemented, achieved a moderate score (0.62), offering a good balance between performance and simplicity. Option B, with limited signal distinction and higher interference, scored lowest (0.42).

Although Option C showed the best performance, Option A is the most practical under current conditions. A hybrid design may offer further improvement in future development.

2 Design Criteria

2.1 Time Consumption

Time consumption reflects how fast the system completes a full ranging cycle with at least three beacons, as required by R1.1 and R2.3. A target of 500ms ensures real-time data flow and alignment with the 1Hz acquisition rate, while anything above 1 second would violate system requirements. The direction of improvement is negative. Designs with efficient scheduling and minimal processing delay are preferable, and this criterion clearly distinguishes low-latency systems suitable for dynamic tracking from slower, buffered ones.

2.2 Computational Simplicity

Computational simplicity is critical due to the STM32 hardware constraint in R1.5. Algorithms must be light enough to run in real time with limited memory and CPU resources. A system utilizing under 30% CPU per cycle is ideal, and anything over 50% risks instability or missed data. The direction of improvement is negative. This criterion helps identify lightweight solutions based on thresholding or simple filters as superior to complex spectral methods that could exceed embedded processing limits.

2.3 Signal Distinction

As required by R1.4, the system must correctly identify signals from multiple beacons without confusion. Using FDMA, signals should be distinguishable with at least 95%

accuracy in noisy settings, and ideally 100% in lab tests. The direction of improvement is positive. This criterion reflects how well each design handles frequency separation and noise rejection, highlighting the effectiveness of modulation, filtering, or decoding schemes in resolving cross-beacon interference.

2.4 Robustness to Noise

Noise robustness determines how reliably the system can operate amid water flow or acoustic interference, as addressed by R1.8 and R2.2. A good system should maintain <10% measurement deviation under ±5dB SNR changes. The direction of improvement is negative. This criterion distinguishes designs using noise-resistant hardware or adaptive filtering from those with high sensitivity to underwater noise, ensuring reliable performance in real-world deployments.

2.5 Scalability

Scalability measures how well the system accommodates more than the minimum three beacons required by R1.1. A target of up to six beacons with no performance loss demonstrates strong design flexibility. The direction of improvement is positive. This criterion helps differentiate modular, dynamic systems that support future expansion from rigid designs that require complete reconfiguration when the beacon count changes.

2.6 Latency

Low-latency ranging is critical to achieving real-time positioning, as required by R1.6 and R2.3. If latency between sonar emission and valid measurement exceeds 300 milliseconds, sensor fusion with IMU and GPS becomes misaligned, degrading tracking accuracy. Studies in underwater robotics (Song et al., 2019, Ocean Engineering) suggest that sonar latency under 100 milliseconds is needed for effective control in fast-moving platforms. The direction of improvement is negative, as lower latency enhances system responsiveness. This criterion helps distinguish designs that can support dynamic operations—such as trajectory following or obstacle avoidance—from those suitable only for static or slow-moving scenarios.

2.7 Power Efficiency

Under R2.6, the system is expected to operate continuously for up to 10 hours on limited battery capacity. Achieving this requires average power consumption to remain below 1 watt, with a target closer to 500 milliwatts. Research on autonomous underwater vehicles (Nakamura et al., 2020) shows that optimizing power via duty-cycled transmission and low-energy microcontrollers significantly extends mission time. The direction of improvement is negative. This criterion favors systems that use interrupt-driven designs, efficient sonar activation, and hardware-level power control over continuously active modules, which are unsuitable for long-range or long-duration deployment.

2.8 Environmental Compatibility

The system must perform reliably in freshwater environments, consistent with R1.10 and R2.1, while minimizing disturbance to aquatic life. High-intensity sonar above 190 dB re 1 μPa has been shown to impact fish behavior (Popper and Hawkins, 2019), making emission levels and frequency selection critical. Additionally, corrosion and fouling can degrade materials over time, so components must use water-resistant coatings and marine-grade enclosures. The direction of improvement is positive. This criterion separates designs that consider long-term deployment and biological impact from those limited to controlled lab conditions.

2.9 Fault Tolerance

As specified in R2.7 and implied by R2.3, the system must continue functioning in the presence of individual component failures, such as the loss of one beacon or data packet corruption. Best practices in resilient navigation systems, such as those used in Saab Sabertooth AUVs, involve graceful degradation strategies where the system falls back to reduced-dimension localization or logs errors while maintaining operation. The direction of improvement is positive. Designs with watchdog timers, redundant data logging, and fallback routines will outperform those that stop functioning upon minor faults, ensuring robustness in unpredictable underwater environments.

2.10 Maintainability

Maintainability is vital for minimizing downtime during field operations and is a key aspect of long-term usability under R2.7. Designs inspired by platforms like BlueROV2, which allow rapid module replacement and firmware updates, have demonstrated that modular architecture significantly improves serviceability. The direction of improvement is positive. Systems that offer accessible connectors, hot-swappable components, and external debugging interfaces enable faster repairs and upgrades. This criterion clearly distinguishes between rigid, experimental setups and field-ready, maintainable designs.

2.11 Security & Data Protection

The system is required to log synchronized sonar and IMU data during each mission, as outlined in R1.9. To prevent data loss or corruption, especially in long-duration or multi-hour deployments, security and integrity of data storage must be ensured. Techniques such as onboard checksums, file system journaling, and encrypted SD card logging, as used in secure UAV systems (Qin, Sensors, 2021), are highly recommended. Furthermore, accidental removal or power loss should not result in unusable logs. The direction of improvement is positive. Designs that implement fault-resistant, secure logging and data validation will outperform those relying on raw storage or unsecured protocols, especially in mission-critical applications such as underwater infrastructure inspection or research.

2.12 User Interface Friendliness

Although not explicitly specified, user interface friendliness is a practical requirement that strongly supports R2.7, which emphasizes system robustness and field usability. Operators in marine environments must be able to quickly deploy, configure, and monitor the system with minimal training. Systems such as those used in ArduSub integrate intuitive visual dashboards and real-time diagnostics, significantly reducing deployment errors. A user interface that shows signal status, ranging performance, and system health through a GUI or serial console enhances usability. The direction of improvement is positive. This criterion helps identify designs accessible to non-experts and practical in field conditions, compared to those that require low-level configuration or lack status feedback.

2.13 Integration Capability

To support real-time underwater localization and data fusion, the system must integrate seamlessly with RTK-GPS, IMU, and SLAM modules, in accordance with R1.2 and R1.9. This requires standardized data formats and interfaces such as UART, CAN, or USB CDC, as well as compatibility with common middleware like ROS. Studies on sensor fusion platforms (Kuutti, 2020) show that integration bottlenecks often arise from inconsistent timing or proprietary formats. The direction of improvement is positive. Designs offering synchronized timestamping, ROS message compatibility, and modular output formats will clearly stand out from isolated systems, facilitating scalability and system-of-systems deployment.

2.14 Modularity

Modularity ensures that different hardware and software components of the system can be independently replaced, updated, or scaled, a quality emphasized in R2.7. It enables cost-effective repair and supports design evolution without full system redesign. Successful modular systems such as the REMUS AUVs employ plug-and-play sonar modules and separate control boards, enabling flexible reconfiguration. Our system should similarly allow the sonar board, power unit, and MCU to be replaced or upgraded without affecting other modules. The direction of improvement is positive. Systems with clean interface layers, hardware abstraction, and physical separation are clearly preferable to tightly coupled architectures.

3 Requirement Matrix Allocations

Step 1 Customer needs & importance (1-5)
Step 2 Benchmark solution (1-5)
Step 3 Planned design (1-5)
Step 4 Requirements Corelation matrix (1,3,9)
Step 5 TPM benchmarking data and target
Step 6 Choose control points for TPM.
Step 7 Enter value of TPM for each concept
Step 8 Read off QFD score

		Design attributes	1	2	3	4	5	6	7	8	
			Time Consumption	Computational Simplicity	Signal Distinction	Robustness to Noise	Scalability	Latency	Power Efficiency	Environmental Compatibility	Fault Toleran
Customer Needs		Importance									
1	System needs to locate underwater robot accurately.	5	9	3	9	3		3			
2	System needs to have no cross talking between beacons.	4	3	3	9	9					
3	System needs to have Real-time tracking while robot is moving.	5	9	3	9	3		9			
4	System needs to avoid transmission error via signal encoding and processing	4	3	3	9	9		3			
5	System needs to cause no damage to the environments.	3								9	
6	System needs to have good underwater performance.	5	3	1	3	3		1		9	
7	System needs to be used for long periods of time.	4	1	3			3	3	1		
8	System needs ot support rapid deployment and calibration without the need for complex debugging.	4	3	3	3		3	3	9		
9	System needs to be able to increase or decrease the number of beacons according to the task requirements.	3			3		9				
10	System needs to provide diagnostic feedback to enable fault detection and system health monitoring.	4	1	3	3	3	3	3			
11	System needs to be easily maintainable and upgradable in the field.	4		3			3				
12	System needs to identify and isolate faulty beacons dynamically during mission.	5	3	3	3	3	3	3			
13	System needs to adapt signal strength dynamically based on environment	3	3	3	3	3	3	3	3		
14	System needs to integrate with remote monitoring platforms	3					3	3			
15	System needs to support intuitive configuration interface for non-technical users	2		3							
16	System needs to provide traceable logs for audit and mission verification.	3		3							
17	System needs to be resistant to biofouling over long deployments	3								9	
18	System needs to allow for easy retrieval or disposal in end-of-life scenarios.	2								3	
19	System needs to allow for signal encryption and access control.	4	1	3	3	3		1	1		
20	System needs to estimate and report its own remaining operating time or battery life.	4	1	3				1	9		

Figure1 Requirement Matrix

As shown in the diagram above, a set of customer needs relevant to the trade-off analysis of the underwater multi-beacon ranging system has been allocated to design criteria. The green area in the diagram shows the correlation between each customer requirement and design attribute using a weighted scale of 1, 3, and 9, representing weak, moderate, and strong correlations respectively. These correlations are used to distribute each requirement's influence across multiple attributes, ensuring that the relative importance of each customer need is preserved during the design evaluation. To avoid bias caused by over-represented attributes, each requirement's total influence is normalized to maintain equal contribution when calculating QFD scores.

The need to accurately locate the underwater robot (Customer Need 1) is directly influenced by time consumption, robustness to noise, and signal distinction, as these criteria together determine the precision and responsiveness of the ranging process. Therefore, these attributes are given strong correlations. Real-time tracking (Customer Need 3) is also strongly affected by time consumption, latency, and robustness to noise, as high-speed updates and low delay are crucial when the robot is moving. To avoid interference (Customer Need 2), signal distinction and scalability are both emphasized, since cross-talk becomes more likely when multiple beacons are deployed concurrently. Thus, high signal fidelity and system expansion capabilities are essential.

For reliable long-term operation (Customer Need 7), power efficiency and scalability are key, as energy management and modular configuration impact mission duration. Similarly, environmental robustness (Customer Need 5) is indirectly expressed through robustness to noise and power efficiency, as underwater systems must

withstand varying acoustic conditions and power constraints.
Rapid deployment and beacon configurability (Customer Need 8) require both computational simplicity and scalability. These features enable fast recalibration and system reconfiguration without excessive complexity. Maintainability and upgradeability (Customer Need 11) are linked with computational simplicity and signal distinction, ensuring that the system remains accessible for fault diagnostics and future improvements.
Security and data protection (Customer Need 19) is mapped to power efficiency and signal distinction, as secure communication protocols add computational load and must maintain signal clarity. Lastly, latency, power efficiency, and time consumption are correlated with the ability to report system health and battery life (Customer Need 20), since real-time feedback and low energy overhead are necessary to support continuous monitoring functions.
Overall, these customer needs were chosen based on their direct relevance to functional performance, robustness, and usability of the system, all of which are critical to the success of a modular underwater beacon-based ranging platform. This structured mapping enables effective QFD-driven concept comparison and ensures alignment between technical design efforts and user expectations.

4 Trade Off Analysis

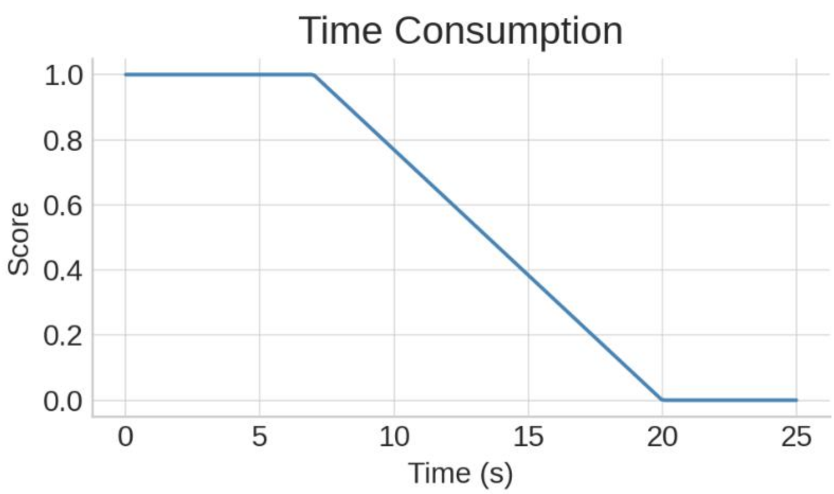
Scheme C uses a multi-frequency beacon communication scheme, in which three beacons can simultaneously transmit sonar pulses at different frequencies. This enables the receiver to distinguish signals based on frequency domain separation without time division multiplexing. This method enables real-time, high-precision underwater positioning and minimizes latency. As a result, it received the highest score of 0.8, thanks to its excellent performance in time consumption, latency, and signal differentiation. However, the use of multiple frequencies requires precise hardware filtering and increases power consumption, which may affect the complexity and electromagnetic compatibility of the system. In the end, our group abandoned this scheme.
Scheme A, which is currently implemented in the project, adopts a single-frequency sequential communication design. Each beacon is assigned a specific time slot for transmission and is identified by embedding ID information in the transmitted data packet. This method ensures no crosstalk between beacons and provides reliable performance under typical underwater conditions. Although its latency is higher than that of Scheme C due to its serial structure, it is easier to implement, has simpler signal processing requirements, and has lower hardware costs. Its score of 0.6 achieves a balance between robustness, simplicity, and scalability.
Option B explores a time-synchronized signal triggering mechanism where all beacons transmit signals simultaneously using the same frequency and rely on arrival time difference and signal strength for positioning. While fast synchronization can be achieved in theory, the design lacks effective signal differentiation and is susceptible

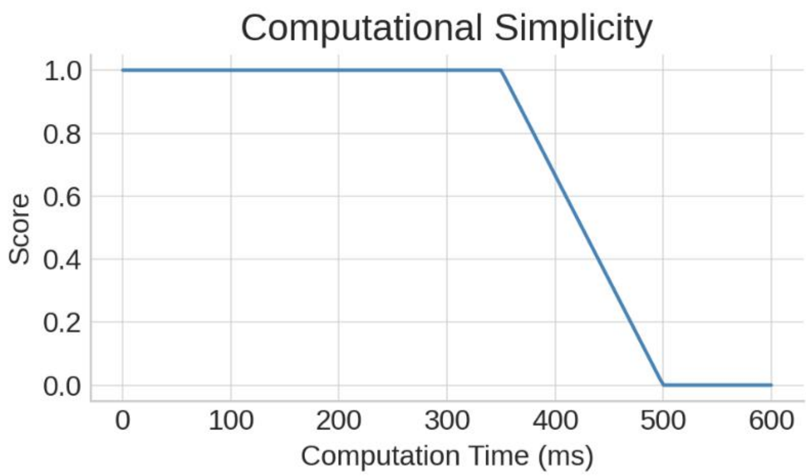
to noise and multipath interference in underwater environments. These challenges increase processing complexity and reduce accuracy. As a result, Option B has the lowest score of only 0.4, with obvious deficiencies in signal robustness and fault tolerance.

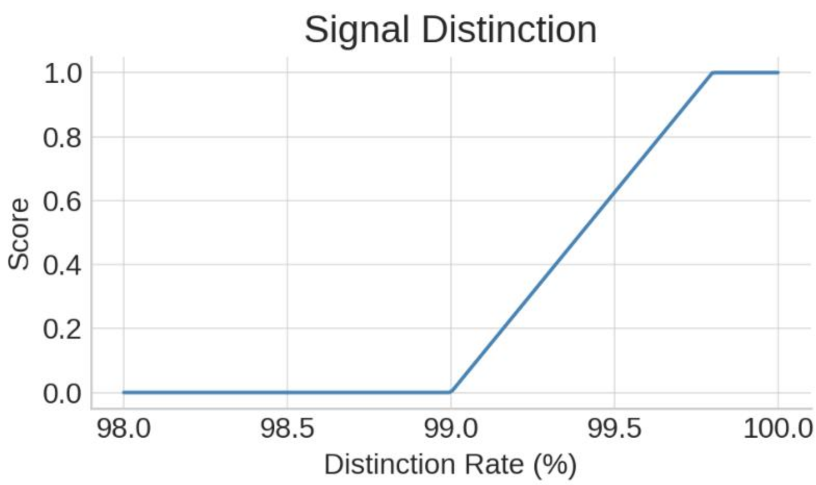
Randomized decision testing confirms that Option C is the highest performing solution under ideal conditions. Although Option A scores slightly lower, it maintains high reliability and is more suitable for actual deployment due to its simpler architecture. Although Option B is conceptually efficient, it has proven to be unsuitable for underwater positioning tasks that require high signal clarity and environmental robustness.

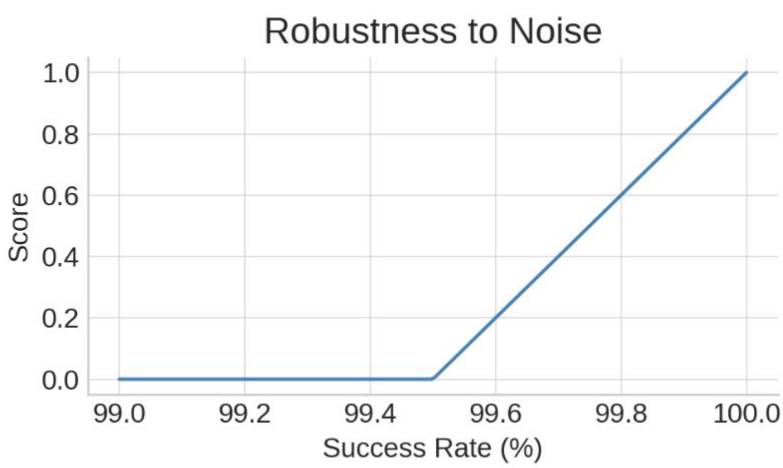
In summary, while Option C represents the best high-performance solution, Option A remains the most practical choice for current applications. To further improve system performance, future designs can consider a hybrid protocol that combines the concurrent tracking advantages of Option C with the energy efficiency and robustness of Option A.

Appendix 1：TPM




Computational Simplicity
1.0
0.8
0.6
0.4
0.2
0.0
Score
0
100
200
300
400
500
600
Computation Time (ms)


Signal Distinction
1.0
0.8
0.6
0.4
0.2
0.0
Score
98.0
98.5
99.0
99.5
100.0
Distinction Rate (%)


Robustness to Noise
1.0
0.8
0.6
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0.2
0.0
Score
99.0
99.2
99.4
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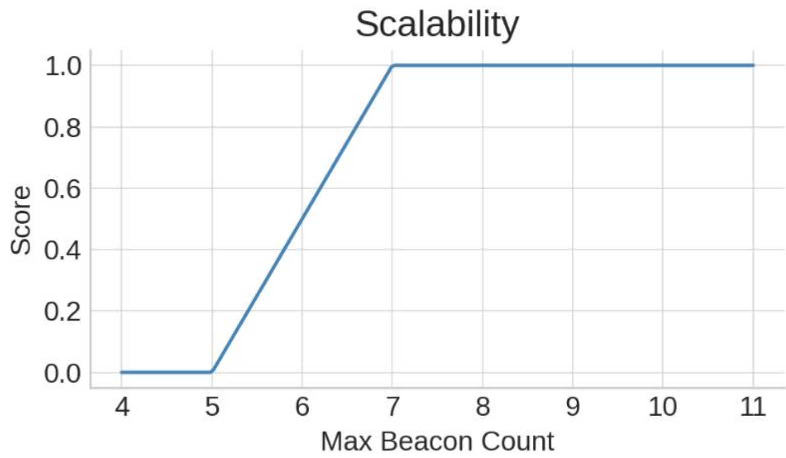
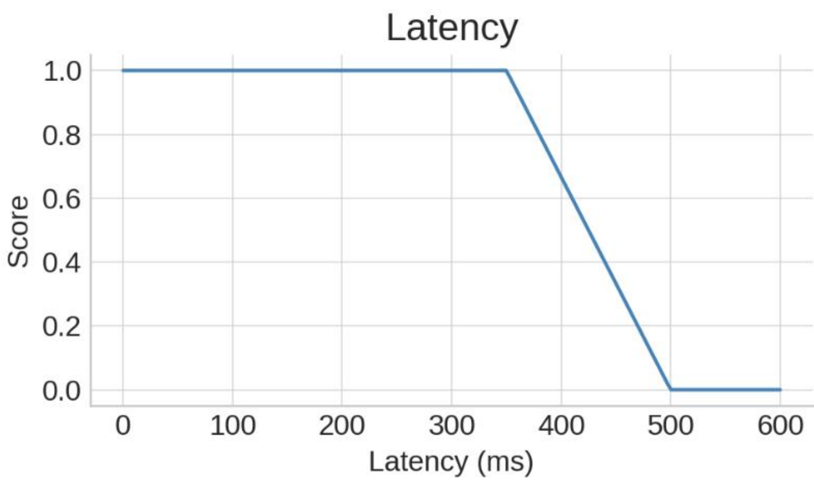
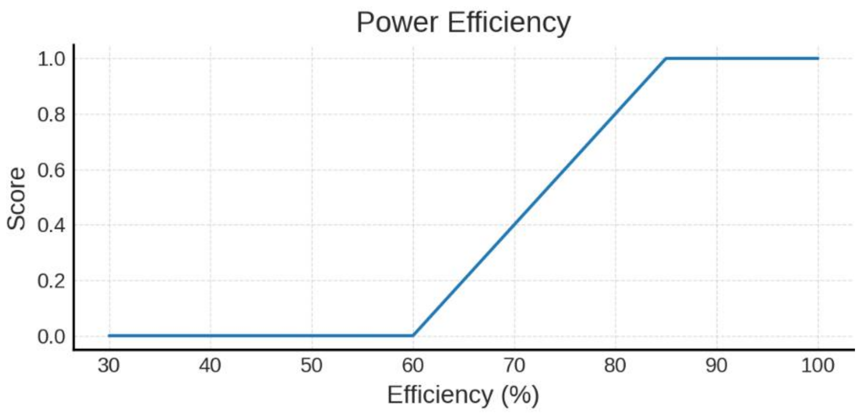
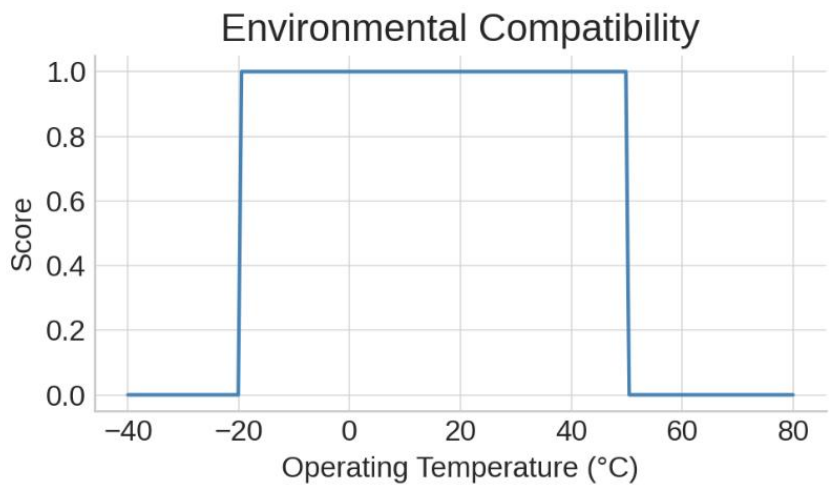
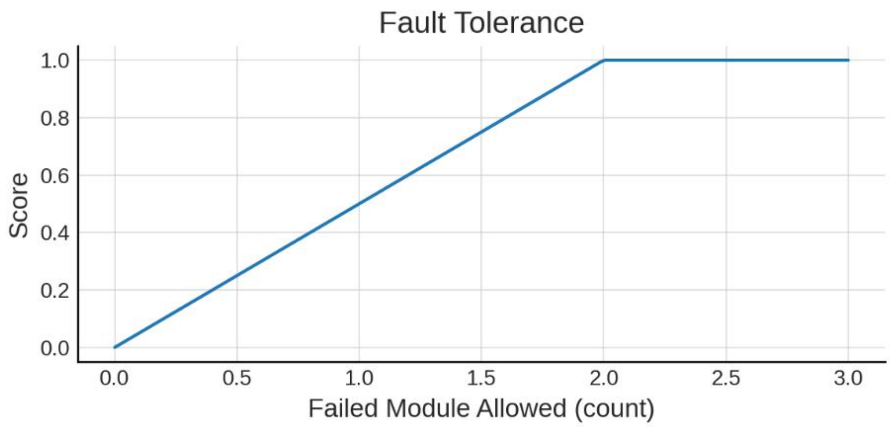
99.8
100.0
Success Rate (%)

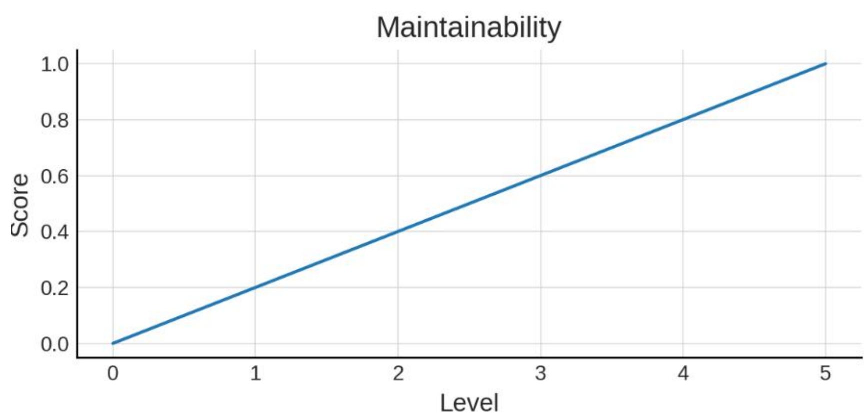

Scalability
Score
1.0
0.8
0.6
0.4
0.2
0.0
4
5
6
7
8
9
10
11
Max Beacon Count

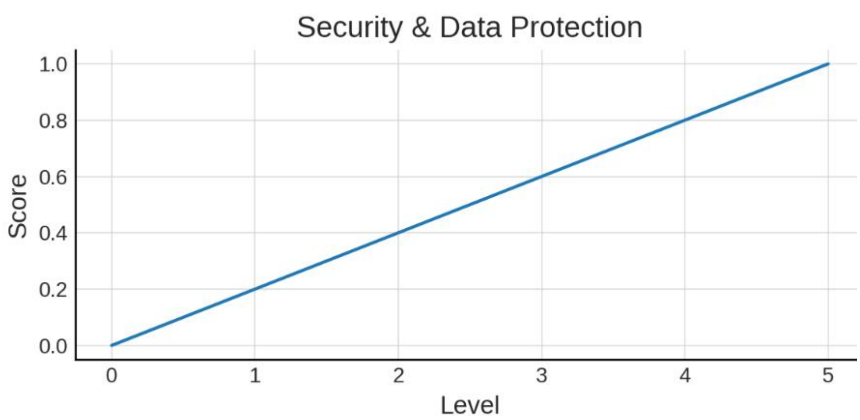

Latency
Score
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
600
Latency (ms)

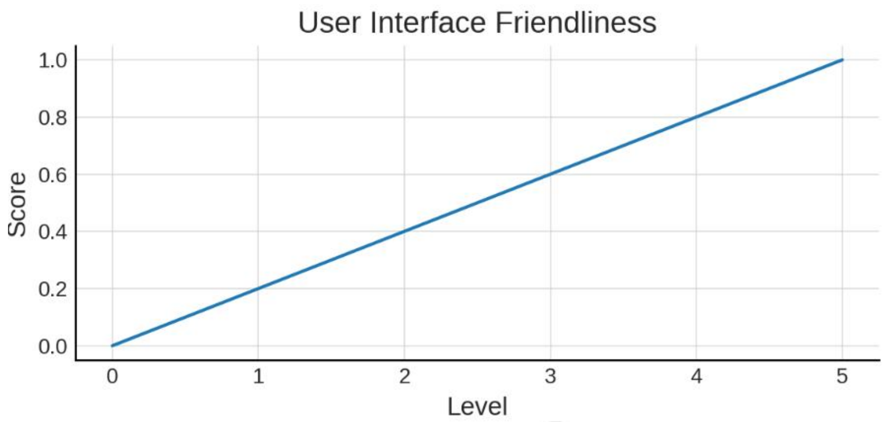

Power Efficiency
Score
1.0
0.8
0.6
0.4
0.2
0.0
30
40
50
60
70
80
90
100
Efficiency (%)

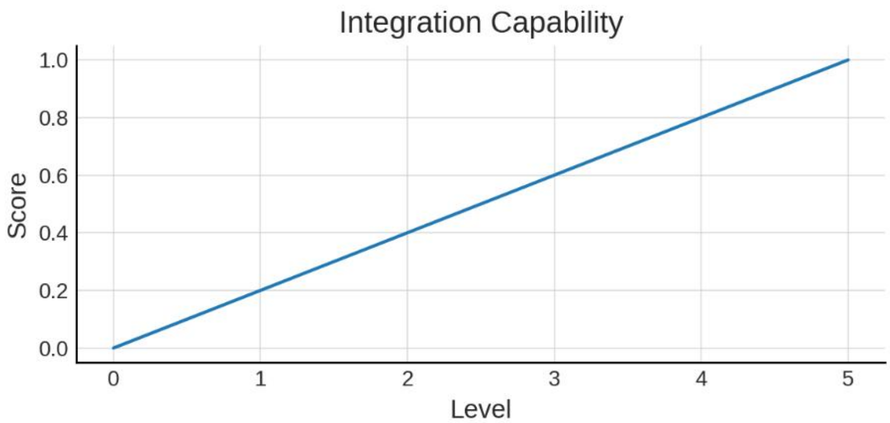

Environmental Compatibility
Score
Operating Temperature (°C)

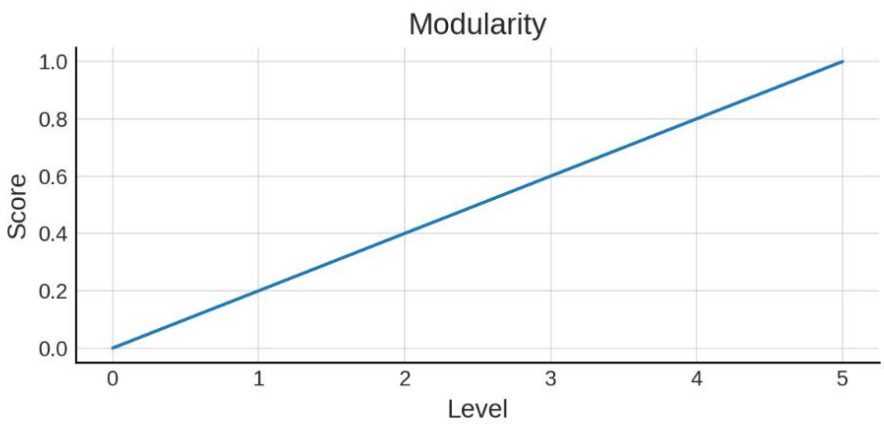

Fault Tolerance
Score
Failed Module Allowed (count)


Maintainability
Score
Level


Security & Data Protection
Score
Level







Appendix 2 List of System Requirements

1. The system shall perform real-time distance measurements one by one to at least three stationary beacons using ultrasonic signals.
    - 1.1 The system shall combine sonar ranging data with RTK-GPS and IMU orientation data to give accurate 3D position.
    - 1.2 The system shall achieve a ranging accuracy of ±50 cm.
    - 1.3 The system shall provide a structured output dataset suitable for 3D underwater SLAM research.
    - 1.4 The system shall implement Frequency Division Multiple Access (FDMA) to distinguish signals from multiple beacons.

1.5 The system shall use computational power that is supported by the stm32 chip
1.6 The system shall support time synchronization mechanisms to ensure sensor alignment.
1.7 The system shall operate at a minimum data acquisition rate of 1Hz (at least one measurement per second).
1.8 The system shall resist background noise from water flow or other sonar systems.
1.9 The system shall record and store synchronized sensor data (sonar, IMU) for processing and analysis.
1.10 The system shall operate in freshwater environments without significant signal degradation.

2 The system shall perform well without error underwater.
2.1 The system shall comply with safety regulations for underwater robotics and sonar equipment and environmental protection laws.
2.2 The system shall maintain stable operation under varying environmental conditions, including minor water flow disturbances.
2.3 The system shall achieve reliable communication with beacons within a range of 100 meters.
2.4 The system shall function at depths of up to 50m meters without performance loss.
2.5 The system shall be capable of continuous operation for at least 10 hours without failure.
2.6 The system shall have redundant data logging to prevent data loss in case of power failure.
2.7 The system shall be designed for easy maintenance and allow replacement of individual sensors or processing units.

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