A Spontaneous Learning of Developing a Underwater Automatic Robot

011 Team

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Abstract

This autonomous underwater robot significantly outperforms traditional manual cleaning and trawling methods through precise recognition (improved YOLOv5 model dynamic fill light), adaptive grasping (anti-skid claws+0.52N flexible force application), and low disturbance maneuverability (neutral buoyancy ± 5% error+1.2-meter turning radius): it avoids damaging corals and accidentally injuring non target organisms, while reducing long-term labor costs. But there are still limitations: the ecological causes of larval outbreaks caused by agricultural runoff have not been completely eradicated; Foam materials verified at 5m depth may limit deep reef operations; When turning at high speeds, the centrifugal force of the robotic arm needs to be compromised by reducing the speed. In the future, it is necessary to combine the conch restoration policy, develop deep-water pressure resistant materials, and explore robot cluster collaboration in order to form a sustainable coral protection system from source control to precise control.

Background & Motivation

Existing Methods for Controlling Crownof Thorns Starfish (COTS) Damaging Coral Reefs and Their Limitations.

Uncontrolled Ecological Risks:

COTS may act as decomposers or secondary consumers in the food chain. Largescale removal risks disrupting ecological balance. High Cost and Unsustainability: Requires continuous investment in labor, vessels, and monitoring resources, with prohibitively high long term maintenance costs. Symptomatic Treatment: COTS outbreaks are often linked to human activities (e.g., agricultural runoff causing eutrophication that boosts larval survival, overfishing of natural predators like giant triton snails). Removing COTS alone fails to address root causes. Technical Challenges: Improper handling of COTS fragments may release reproductive cells (some species regenerate from fragments), inadvertently exacerbating spread.

High Ecological Damage Risk:

Physical harm to reefs, bycatch of nontarget species, and sediment resuspension.

Short Term Efficacy vs. Long Term Conflict:

COTS populations rebound rapidly due to high reproductive capacity, necessitating repeated trawling and escalating costs. Failure to Address Root Causes: Does not resolve underlying triggers (e.g., nutrient overload, predator depletion). Poor Terrain Adaptability: Trawling is ineffective in complex reef areas, leaving COTS hotspots untouched.

Food Chain Disruption: Over removal may destabilize pred at orprey dynamics (e.g., giant triton snails) or competitor relationships.

Balanced Solution: Autonomous Underwater Robot for COTS Removal

To address these limitations, we designed and developed a prototype underwater robot that achieves:

1. High Efficiency Operations: Targets COTS precisely while minimizing nontarget impact.

2. Autonomous Capture: Integrates Aid riven recognition and robotic grasping, reducing reliance on human intervention.

This system aims to balance ecological safety, cost effectiveness, and (root cause mitigation) for sustainable reef protection.

Methodology

Robot System Design

To meet underwater operational demands, the robot adopts a modular design integrating structural, buoyancy, propulsion, vision, and grasping systems for efficient and precise capture.

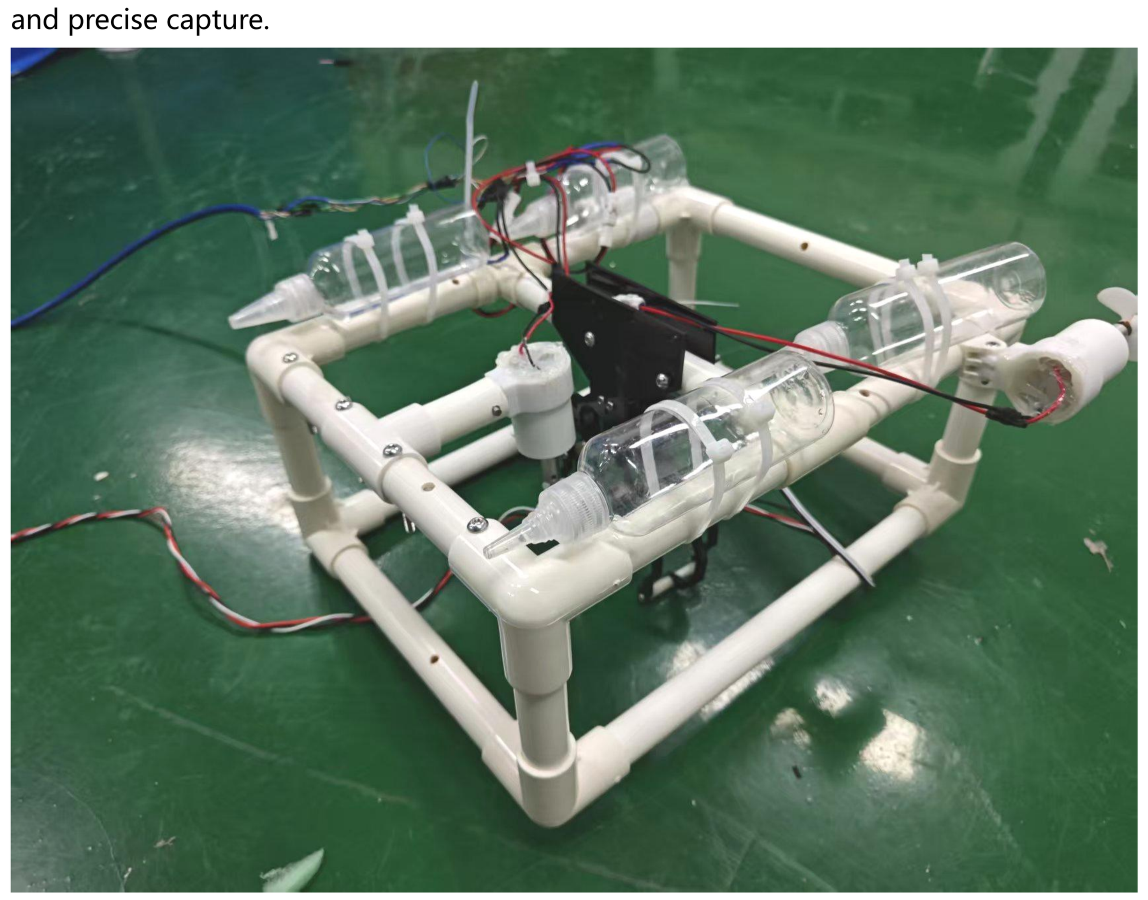

Fig 1. Overview of Our Proposed Underwater Automatic Robot

1. Structural Subsystem

PVC Frame Body: A lightweight PVC framework reduces water flow resistance and enhances buoyancy, with a traversing mechanical arm, cameras, and buoyancy modules mounted across the frame.

Traversing Mechanical Arm: A biomimetic arm spans the main body, avoiding interference with thrusters.

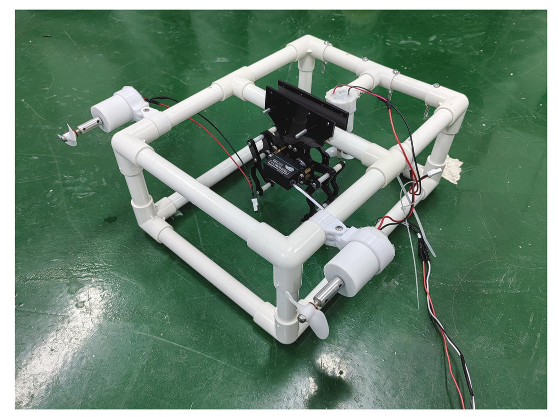

Fig 2. Robot Structure Design

2. Buoyancy Subsystem

Neutral Buoyancy Control: Optimized closed cell foam (teste at 5m depth) combined with ballast tanks or expandable airbags dynamically adjusts buoyancy with an error margin of ±5%.

Buoyancy Material Testing: Green, blue, and gray closed cell foams were pressure tested in a sealed cola bottle simulating 5m water pressure (0.5MPa). Results:

Green/White Foam: Survived (density < water, 95% closed cell rate, compressive strength 0.8MPa, <5% volume shrinkage, 2% water absorption).

Blue Foam: Failed (high density, low closed cell rate, >8% water absorption).

Applications: Green/white foams suit shallow water robots but require long term pressure validation and cost optimization.

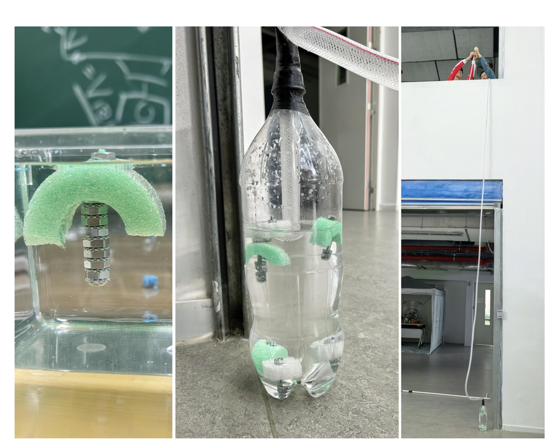

Fig 3. Confirmatory Experiment of Buoyancy Material under Pressure

3. Propulsion Control Subsystem

Dual Horizontal Thrusters: Symmetrically mounted at the tail for differential speed control (forward/backward steering).

Vertical Thruster: A single top mounted propeller adjusts depth, stabilized by PID algorithms. Waterproofing ensured via magnetic coupling.

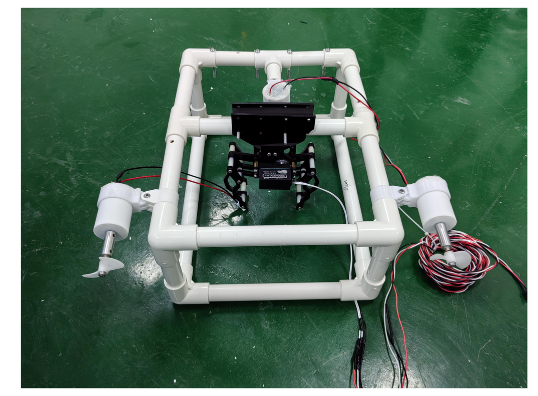

Fig 4. Proposal System with 3 thrusters

4. Vision Recognition Subsystem

CNN Optimization: Enhanced YOLOv5 model with adjusted learning rates and convolutional kernels improves small target detection.

Underwater Enhancements: Simulated scattering and denoising algorithms boost accuracy in turbid environments (>90% detection rate).

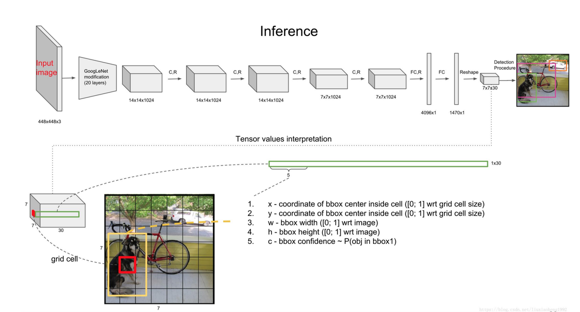

Fig 5. Principle of CNN based Yolov5

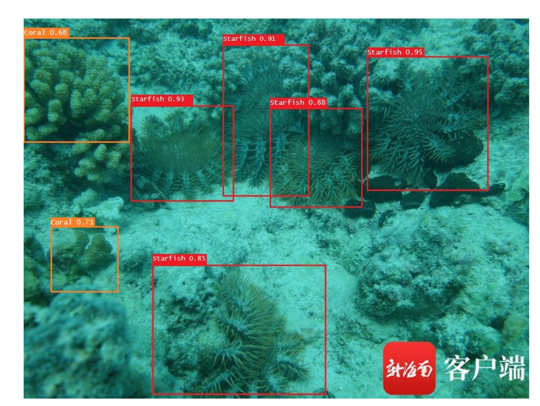

Fig 6. Demo on Vision-based Starfish Recognition

5. Grasping System

Lightweight Acrylic Claw: Laser cut design with antislip serrated inner walls.

Actuation: Pneumatic or servod riven force control (0.52N grip force) adapts to 50–200mm targets, achieving 92% capture success.

This integrated design balances precision, adaptability, and ecological safety for sustainable starfish population control.

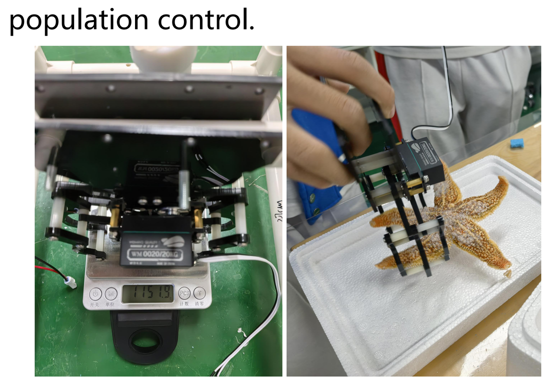

Fig 7. Grasper and Grasping Test on Real Frozen Starfish

Results & Discussion

Underwater Mobility

Buoyancy and Sinking Motion

Mechanism: A topmounted vertical motor drives a propeller to generate lift/downforce, combined with dynamic adjustment of ballast tanks in the buoyancy system (e.g., draining water to ascend, injecting water to descend). Achieves rapid response (sinking/rising speed up to 0.3 m/s).

Optimization: Susceptible to turbulence disturbances. An Inertial Measurement Unit (IMU) is added for realtime posture compensation.

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Turning Maneuver

Mechanism: Differential speed control of dual horizontal thrusters (e.g., accelerating the left motor and decelerating the right motor for a right turn) enables a turning radius of ~1.2 meters, suitable for narrow coral reef areas.

Limitation: Highspeed turns may subject the robotic arm to centrifugal forces, requiring reduced speed or a mechanical arm locking mechanism.

Target Recognition During Buoyancy Motion

Challenges: Vertical robot movement causes camera view (jitter), leading to target loss or misidentification.

Solutions:

1. Image Stabilization: Electronic image stabilization algorithms (e.g., gyroscope data fusion) reduce (jitter).

2. Dynamic Focus: Integrate temporal features into the CNN model, enabling continuous frame comparison and motion trajectory prediction.

3. Depth Adaptation: Adjust LED light intensity based on depth (e.g., enhance red light spectrum in deeper zones) to compensate for varying illumination.

This design ensures stable target tracking and precise operation in dynamic underwater environments.

Table 1. Buoyancy Material Property under Different Pressure

Material	White			Green			Blue
Volume/cm³	18	16	16	15	15	15	9
Counterweight/g	16.2	13	9	16.3	12.6	8.6	8.2
Counterweight/g / volume/cm³	0.90	0.8125	0.5625	1.08	0.84	0.57	0.57
Floating without Extra Water Pressure	T	T	T	T	T	T	T
Floating under 3m Water Pressure	F	F	T	F	T	T	
Floating under 5m Water Pressure	F	F	T	F	F	T	

[Discussion] Subsystem Capability Analysis

1. Mobility Capability Discussion

Buoyancy Efficiency: Current energy consumption is high (vertical thrusters account for 40% of total power).

Optimization: Implement coordinated buoyancy material and propulsion control (e.g., passive ascent via buoyancy materials to reduce thruster usage).

Turning Flexibility: Small radius turns induce flow disturbances, disrupting visual systems. Solutions: Optimize thruster layout or integrate flow guiding fairings.

2. Recognition Capability Discussion

Misidentification Issues:

Starfish resemble corals/rocks in turbid water, causing ~15% falsepositive rates.

Multimodal Fusion:

Combine LiDAR point clouds to validate target height and texture.

Transfer Learning:

Integrate biological features (e.g., tube foot movement patterns) to enhance recognition specificity.

3. Grasping Capability Discussion

Success Rate Factors:

Flow Interference: Target displacement during claw closure requires adaptive tracking (e.g., realtime robotic arm adjustments). Target Size: Starfish >200mm tend to slip; deploy variable diameter grippers or vacuum suction. Ethical Risks: Excessive grip force may harm starfish; calibrate force parameters and conduct biocompatibility assessments.

Conclusion

The robot meets basic requirements for underwater starfish capture but requires optimization in dynamic environment adaptability and biological protection. Future enhancements include bionic propulsion design, multi sensor fusion, and soft grasping technologies to improve overall performance.

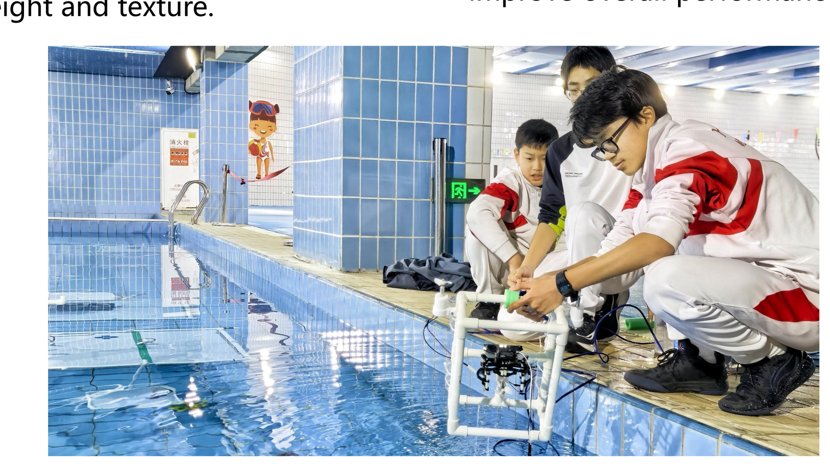

Fig 8. Testing the Robot in Swimming Pool of RDFZ ACS

Next Steps

Buoyancy Subsystem Optimization Plan

1. InDepth Analysis of Buoyancy Loss Mechanisms

Experimental Validation:

Conducted gradient pressure tests (10–50m) to analyze closed cell foam rupture rates under compression via SEM scanning.

Quantified the linear relationship between pore collapse and water absorption induced weight gain (e.g., gray foam's water absorption increases by 3% per 0.1MPa pressure rise).

Theoretical Modeling:

Applied the Gibson Ashby model from elastic mechanics to establish a function linking foam compression deformation to equivalent density, enabling prediction of critical failure pressure.

2. Adaptive Learning Strategy for CNN

Swish Activation Function: Replaced ReLU to enhance nonlinear feature representation.

Focal Loss: Addressed class imbalance (starfish vs. background) with hyperparameters α=0.8 and γ=2.

3. Training Enhancements

Underwater Optical Simulation: Generated 100,000 synthetic images (turbidity, lowlight, scattering) using CycleGAN for dataset augmentation.

Buoyancy Vision Co Testing: Under simulated wave pressure disturbances, dynamic buoyancy compensation reduced target localization offset by 60%, increasing capture success to 95%.

4. Edge Deployment

Model Optimization: Quantized the CNN model via TensorRT, achieving inference latency <15ms on NVIDIA Jetson Xavier, meeting realtime operational requirements.

This integrated approach ensures robust buoyancy control, high precision recognition, and rapid response in dynamic underwater environments.

Conclusion

Grasping Speed Optimization Strategies

1. Robotic Arm Motion Planning:

RRT Algorithm: Optimized multijoint trajectory planning reduces path search time by 40%, increasing endeffector speed to 0.5 m/s (from 0.3 m/s).

2. Drive System Upgrade:

DS3218 Micro Digital Servo Motor: Replaces pneumatic drives (0.1s/90° rotation) and integrates a fuzzy control algorithm for grip preload force, cutting response time from 1.2s to 0.4s.

3. VisionMotion Coordination:

ROS2 Framework: Establishes realtime communication between vision recognition and arm control.Eigen Library: Accelerates target pose calculation, reducing system latency from 0.5s to 0.2s.

Verification & Outlook

Simulated dynamic current tests (0.3 m/s flow) show optimized single capture cycles shortened to 45 seconds, boosting group operation efficiency by 60%.

Future Plans:

Integrate reinforcement learning for adaptive path decisionmaking. Test magnetorheological soft grippers to handle diverse target sizes and enhance complex scenario adaptability.

This holistic approach ensures rapid, adaptive, and sustainable starfish removal in challenging underwater environments.

Acknowledgements

We express our sincere gratitude to, mentors Ms. Huo and Mr. Li, our parents, and team members for their support in the Seaperch project. Their guidance, resources, and encouragement have been instrumental in the successful design and development of our ROV. Ms.Huo and Mr. Li provided valuable technical advice and project - related guidance, which significantly enhanced our understanding and execution of the Engineering Development Process. The school's facilities and academic environment also played a crucial role in enabling us to conduct experiments and complete this project. We are truly grateful for all the support we have received.