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A Lobster Claw-Inspired Multifunctional Tool for Underwater Grasping: Design and Simulation Insights

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Abstract: Underwater tools often face challenges in grasping objects effectively, as water resistance and buoyancy can undermine their precision and grip strength. In contrast, the American lobster (Homarus americanus) has claws that skillfully manage these obstacles, effortlessly holding onto a wide range of items in marine environments. Drawing on prior research into lobster-inspired designs, this study unveils a new tool that merges rigid and flexible components to boost underwater performance. The flexible part, crafted from silicone such as Dragon Skin 10, mirrors the serrated teeth of the lobster's claw for reliable gripping, while a gear system with multiple interlocking gears ensures accurate control over force and positioning. Developed in three phases—first copying the claw's shape, then fine-tuning its size, and finally enhancing its function, the tool excelled in tests using objects from the Evolved Grasping Analysis Dataset (EGAD), surpassing standard designs with higher success rates and less effort. It shows great potential for deep-sea exploration and underwater repairs, though its real-world durability, particularly the gear mechanism, awaits confirmation through ocean trials.

Keywords: Biomimicry, Underwater tool, Lobster claw, Grasping

1. Introduction

The American lobster (*Homarus americanus*) possesses claws that exemplify nature's engineering, adeptly tailored to the dynamic conditions of underwater environments. The cutter claw, elongated and equipped with serrated edges, efficiently slices through softer materials such as fish or seaweed, while the crusher claw, broader and lined with molar-like teeth, effectively breaks apart clams or crabs. Research by Elner and Campbell [1] measured these claws exerting a force of 256 Newtons, a capability attributed to a lever system that transforms muscle strength into powerful gripping action through precise structural design. Amid ocean currents and buoyancy, securing objects consistently proves challenging, yet the lobster's claw achieves this with remarkable reliability. For marine tasks, such as retrieving lost equipment or repairing seabed infrastructure—this biological model provides a valuable foundation for innovation. The functionality demonstrated by a lobster splitting a mussel on a rugged rock surface underscores the durable and precise capabilities that engineers aim to emulate.

Bioinspired robotics draws on natural mechanisms to address complex engineering challenges, particularly in demanding environments such as deep ocean settings. The lobster claw, with its combination of substantial force and adaptable flexibility, serves as a valuable model for this discipline. Researchers applied this concept by developing soft robotic fingers featuring claw-like teeth, which demonstrate enhanced gripping performance in aquatic conditions compared to many

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alternatives [2]. Webb [3] explored the potential for robotic systems to replicate the precision of biological organisms, establishing an intellectual foundation for such advancements. Triantafyllou, M. S. and Triantafyllou G. S. [4] previously demonstrated how fish tail structures improve underwater propulsion, setting a precedent for tools inspired by claw functionality. This study builds on that foundation, aiming to adapt the claw's capabilities for applications such as retrieving artifacts from shipwrecks or managing delicate coral specimens.

This research introduces an innovative underwater gripping tool modeled on the lobster claw, integrating a titanium frame for durability, silicone tips for flexibility, and a gear system for precise control. Simulations suggest significant improvements over existing designs, indicating potential applications in marine engineering—such as pipeline repairs—or salvage operations to recover submerged objects. Stuart [5] demonstrated that bioinspired designs can reduce expenses in challenging environments, reinforcing the practical value of this approach. By combining a robust framework with an adaptable grasp, the tool addresses common difficulties encountered in underwater equipment, positioning it as a reliable option for deep-sea tasks. The design seeks to translate nature's refined adaptations into a functional solution capable of performing effectively in turbulent aquatic conditions.

2. Literature Review

2.1. Current Research on Lobster Claw Structure

Extensive research has been devoted to unraveling the mechanics of the lobster claw over time, yielding a comprehensive understanding of its remarkable capabilities. Elner and Campbell [1] examined the crusher claw's structure, demonstrating how its lever mechanism amplifies force to 256 Newtons with growth, offering valuable insight for designing tools requiring significant strength. Zhang [2] applied this knowledge practically, developing soft robotic fingers modeled on the claw's tooth arrangement, which exhibited superior performance in aquatic environments. Herrick [6] provided an early detailed account, describing how the seizer claw's sharp teeth close rapidly to secure prey. Barshaw [7] contributed further perspective, investigating the claw's role in defense against predators, highlighting its multifunctional nature beyond feeding. Collectively, these findings establish the claw as a dependable foundation for tools engineered to deliver robust and adaptable performance in demanding marine conditions.

2.2. Underwater Gripping Tools Overview

The array of underwater gripping tools encompasses a broad range of capabilities, though no single design has achieved optimal performance. Rigid grippers, constructed from materials such as steel, exert consistent force but falter when handling irregular objects like twisted cables or rough stones, as noted by Mazzeo [8]. Flexible systems, typically made of silicone, conform effectively to various shapes yet struggle with heavier loads, according to Galloway [9]. Hydraulic mechanisms provide substantial strength in deep water, but their bulk poses challenges in confined spaces [10]. Pneumatic tools offer a lightweight alternative, though they degrade quickly in saltwater, and battery-powered variants deplete rapidly [11]. Advanced robotic arms with flexible components deliver precise control, but their high cost and maintenance demands present significant drawbacks [12]. Mazzeo [8] concluded that a critical gap remains: a tool combining strength and versatility. The lobster claw, adeptly balancing both attributes, emerges as a promising model to address this deficiency.

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3. Methodology

3.1. Design Principles

The tool's structure draws directly on the lobster claw's inherent advantages. A titanium alloy frame provides robust resistance to substantial loads, mirroring the claw's durable exoskeleton, as documented by Elner and Campbell [1]. Silicone tips, fashioned from Dragon Skin 10, replicate the seizer claw's serrated teeth, enabling secure attachment to objects ranging from smooth pebbles to irregular branches [2]. A system of nested gears, consisting of three or four tightly interlocked components, ensures precise regulation of force and positioning, adjustable from minimal pressure to firm clamping as required. The design evolved through three stages: initial outlines derived from claw dissections, refinements in SolidWorks to optimize dimensions, and a final adjustment incorporating natural principles—streamlining contours for efficient movement through water. Each modification aimed to enhance performance against the challenges of marine environments, reflecting the claw's proven adaptability.

3.2. Simulation Methods

The evaluation process relied on comprehensive simulations to assess the design's viability. Finite Element Analysis (FEA) conducted in ANSYS applied a force of 300 Newtons to the frame, comparing it to established claw force standards [1]. Bieze [13] confirmed FEA's effectiveness in analyzing flexible components such as the silicone tips, ensuring alignment with calculated values. Computational Fluid Dynamics (CFD) performed in COMSOL Multiphysics addressed water flow dynamics, optimizing drag reduction through Navier-Stokes equations, facilitating smooth passage through fluid environments [14]. Multi-physics modeling integrated these elements, benchmarking performance against existing tool data [8]. Extensive adjustments to tip flexibility and gear alignment over several days refined the design for robust operation in challenging marine conditions.

4. Results

4.1. Performance Metrics

The simulation results demonstrated notable performance. Gripping success reached 92.5%, surpassing rigid grippers at 75.3% and flexible counterparts at 80.1%. Maximum force achieved 300 Newtons, sufficient for most applications, while requiring 15% less energy than hydraulic systems. Silicone tips, modeled on the claw's tooth structure, securely grasped irregular objects, including smooth pebbles and uneven forms [2]. Drag remained minimal, enabling efficient movement through water, as supported by fluid dynamics principles [4]. Virtual tests on pipes and rocks revealed consistent reliability in scenarios where other designs faltered, indicating strong potential for deep-sea operations.

4.2. Comparative Analysis

To provide a clear and quantitative evaluation of the bioinspired tool's performance, a comparative analysis was conducted against three established types of underwater gripping tools: rigid grippers, flexible manipulators, and hydraulic tools. This analysis, summarized in Table 1, is derived from simulation data that models each tool's behavior under standardized conditions to ensure a fair and consistent comparison. The table encapsulates five key performance metrics: success rate, maximum force, energy efficiency, adaptability, and drag. Each metric has been carefully selected to reflect critical aspects of underwater tool functionality, offering a comprehensive overview of how the bioinspired design measures up against conventional alternatives.

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Table 1: Comparative Analysis

Metric	**Bioinspired Tool**	**Rigid Gripper**	**Flexible Manipulator**	**Hydraulic Tool**
Success Rate	92.5%	75.3%	80.1%	85.0%
Max Force (N)	300	250	150	400
Energy Efficiency	High (15% savings)	Moderate	Low	Low
Adaptability	High	Low	High	Moderate
Drag	Low	High	Moderate	High

The data presented in Table 1 originates from a series of simulations designed to replicate real-world underwater conditions. These simulations utilized the Evolved Grasping Analysis Dataset (EGAD), a standardized collection of objects for testing, to evaluate each tool's performance in grasping and retaining items of varying shapes, sizes, and textures. This dataset ensures that comparisons are based on consistent criteria, eliminating biases that could arise from differing test conditions. Each tool was subjected to identical simulation parameters, including water density, current velocity, and object placement, to maintain uniformity. The success rate was calculated as the percentage of successful grasps out of 100 attempts per object type, with a total of 10 different objects tested. Maximum force was determined by incrementally increasing the applied load until the tool failed to maintain its grip. Energy efficiency was assessed by measuring the power consumed during each grasping attempt and averaging the results across all trials. Adaptability was evaluated qualitatively by observing the tool's ability to adjust its grip based on object feedback, while drag was computed using computational fluid dynamics (CFD) models to simulate water flow around the tool during movement.

4.2.1. Detailed Explanation of Table 1 Metrics

The following sections elaborate on each metric included in Table 1, providing insight into their significance and the performance of the tools under evaluation:

(1) Success Rate

This metric, expressed as a percentage, quantifies the reliability of each tool in securely grasping and retaining objects across a diverse range of shapes and sizes. A higher success rate indicates greater versatility and dependability in varied underwater scenarios. The bioinspired tool achieved a success rate of 92.5%, significantly exceeding the rigid gripper (75.3%), flexible manipulator (80.1%), and hydraulic tool (85.0%). This enhanced performance is attributed to the hybrid design, which integrates the precision of rigid structures with the conformability of flexible materials, enabling effective adaptation to various object contours.

(2) Maximum Force

Measured in Newtons, this metric represents the peak gripping strength each tool can exert. The bioinspired tool recorded a maximum force of 300 N, which, while lower than the hydraulic tool's 400 N, surpasses the rigid gripper (250 N) and flexible manipulator (150 N). This level of strength positions the bioinspired tool as a suitable candidate for tasks requiring substantial force, without the added complexity and bulk associated with hydraulic systems.

(3) Energy Efficiency

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Categorized qualitatively, this metric reflects the power consumption of each tool relative to its output. The bioinspired tool is rated “High”, indicating a 15% reduction in energy use compared to the hydraulic tool, which is rated “Low”. This efficiency results from an optimized design that minimizes unnecessary energy expenditure through precise control mechanisms. In contrast, the rigid gripper and flexible manipulator are rated “Moderate” and “Low”, respectively, underscoring the bioinspired tool’s advantage in sustainable operation, a critical consideration for prolonged underwater missions.

(4) Adaptability

This metric evaluates the capacity of each tool to handle a wide array of object types and environmental conditions. Both the bioinspired tool and the flexible manipulator are rated “High”, highlighting their shared strength in versatility. The rigid gripper and hydraulic tool, rated “Low” and “Moderate”, respectively, demonstrate less capability in adjusting to irregular or delicate objects. The bioinspired tool’s adaptability is enhanced by its silicone tips, which emulate the lobster claw’s ability to conform to various surfaces, thereby reducing the risk of damage to fragile items.

(5) Drag

This metric measures hydrodynamic resistance, and affects the tool’s maneuverability and speed in water. The bioinspired tool exhibits “Low” drag, facilitating swift and efficient movement, a characteristic inspired by the streamlined forms of marine organisms. In contrast, the rigid gripper and hydraulic tool both experience “High” drag, potentially impeding their agility in dynamic underwater environments. The flexible manipulator, rated “Moderate”, occupies an intermediate position but does not match the bioinspired tool’s optimized fluid dynamics.

4.2.2. Implications of the Comparative Analysis

Table 1 demonstrates the bioinspired tool’s competitive performance across multiple dimensions. Its high success rate and adaptability render it particularly suitable for tasks involving diverse or unpredictable objects, while its energy efficiency and low drag enhance operational longevity and responsiveness. Although its maximum force does not reach the level of the hydraulic tool, the bioinspired design achieves a favorable balance between strength and versatility, making it a promising option for a wide range of underwater applications.

4.3. Simulated Scenarios

Two simulated real-world scenarios were evaluated: lifting a 50 kg object from a depth of 20 meters and grasping a rough coral fragment. The bioinspired tool successfully completed both tasks, hoisting the load with stability and securing the coral without causing damage. These outcomes highlight its capability to handle both heavy-duty and delicate operations effectively.

5. Conclusion

This lobster claw-inspired tool combines a robust titanium frame, flexible silicone tips, and a gear-based mechanism to achieve precise control, demonstrating exceptional performance in simulations with a gripping success rate of 92.5%, a maximum force of 300 Newtons, and enhanced energy efficiency compared to conventional designs. Drawing on foundational research by Elner and Campbell [1], which quantified the claw’s force at 256 Newtons, and Zhang [2], who adapted its tooth structure for robotic applications, the design proves well-suited for marine engineering tasks, such as pipeline repairs, and salvage operations, including the recovery of submerged anchors. The integration of rigid and flexible components ensures reliable operation under the demanding

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conditions of underwater environments, offering a promising solution where traditional tools often falter.

Despite these strengths, simulations reflect controlled settings that do not fully capture the complexities of real aquatic conditions, such as turbulent currents or debris accumulation, which could affect performance, as noted by Bieze [13]. The tool's current dimensions are effective for its intended scope, yet adapting it to larger or smaller scales necessitates additional refinement. Durability in practical scenarios, particularly against corroded shipwrecks or extended saltwater exposure, remains untested and requires field trials to confirm, a point underscored by Kim et al. in their analysis of soft robotics longevity.

Future enhancements might incorporate corrosion-resistant alloys to bolster resilience, integrate adaptive control systems for real-time responsiveness, or involve testing in deeper waters to expand its operational range, aligning with Webb's [3] vision of bioinspired evolution in robotics. Researchers [5] argue that such designs advance with material innovations, suggesting significant growth potential. Applications span retrieving shipwreck artifacts, inspecting coral ecosystems, and conducting underwater repairs, with the tool's ability to manage irregular shapes making it valuable for scientific and industrial endeavors, as emphasized by Laschi [11].

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