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Biomimetic design of a microplastic-absorbing robot for recycling detection application in aquatic environments

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Abstract. Microplastic pollution in global aquatic ecosystems poses an imminent threat to both ecological integrity and human wellbeing. These minuscule particles (< 5 mm), derived from anthropogenic activities, accumulate organic pollutants and heavy metals, permeating the food chain and triggering reproductive abnormalities and endocrine disruption in organisms. Particles with diameters smaller than 100 μm are particularly insidious, owing to their diminutive size, which facilitates greater bioaccumulation while rendering them significantly more challenging to collect and detect. Drawing inspiration from the highly efficient filtration mechanism of sabellid worms, this study proposes the design of an aquatic microplastic adsorption robot that mimics the feather-like radiolar crown structure of these organisms. The robot incorporates a flexible polymeric vibrating membrane system, a solid monolithic magnetic porous polymer material (PDVB-Fe_3O_4), and underwater adsorption suction cups to achieve efficient capture of minute microplastics (diameters less than 100 μm). Post-collection, the adsorption module enables rapid desorption, thereby facilitating facile onshore analysis and detection. The authors adopted Computational Fluid Dynamics (CFD) methods to develop a fluid-solid coupling model, simulating five water environments with varying flow velocities: 0.05 m/s, 0.07 m/s, 0.09 m/s, 0.2 m/s, and 0.5 m/s. The results validated the robotic system's in-water performance, revealing low energy consumption and favorable stability (data). This design offers a scalable technical solution for achieving the Sustainable Development Goal 14 (SDG14) target.

Keywords: microplastic absorption, water body inspection, bionic robot, environmental remediation

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1. Introduction

Microplastic pollution has emerged as a pressing and pervasive threat to global aquatic ecosystems. These tiny plastic particles, with diameters less than 5 mm, persistently adsorb organic pollutants and heavy metals, permeating the food chain and inducing reproductive abnormalities in aquatic organisms as well as risks to human health [1]. Currently, trillions of microplastic particles are present on ocean surfaces; for instance, in the Yangtze River estuary, seawater contains 2,000–6,000 microplastic particles per cubic meter. Among these, a substantial proportion consists of even smaller particles (diameters less than 100 μm), which are more readily ingested by organisms than larger counterparts. Simultaneously, their minuscule size renders them significantly more challenging to collect and detect [2]. A considerable proportion are sub-100 μm particles that get into organisms more easily than the larger ones, and, because it is too small, it is more difficult to collect and detect [3]. Current sampling techniques, such as trawl and pump sampling employed in seawater monitoring, suffer from inherent limitations. The trawl sampling method is highly susceptible to the environment (influenced by waves or wind, the trawl water level will be higher or lower than the mark, leading to deviations in trawl depth from the target mark and discrepancies between actual and calculated sampling volumes: the average volume of each sample at the middle depth marker is estimated to be $62m^3$, volume of too low mining volume is $47m^3$, too high actual sample volume is $78m^3$ [4]). Pump sampling, on the other hand, is constrained by limited sampling area and volume, which can lead to the misestimation of microplastic abundance: smaller sampling volumes for pump sampling result in fewer particles per sample, resulting in increased variability when recalculating concentrations. For instance, Karlsson et al. calculated that the pump sample concentration is 0~0.4 microplastics/m^3, trawl sampling concentration is 0.18~0.92 microplastics/m^3 [4]); The filter screen in the filter device in the electric pump used in the sampling of wastewater microplastics needs to be changed several times according to the size of different microplastics;Trawl sampling is also restricted in freshwater environments due to vessel size constraints [2]. Thus, there is an urgent need for innovative technologies to mitigate these limitations. This study takes inspiration from the biological filtration mechanism of fan worms (Annelida: Sabellidae). Fan worms filter microparticles via their feather-like radiolar crown structures, where ciliary oscillations drive water flow and mucus nets facilitate the efficient capture of particles, exhibiting exceptional efficiency for minute particles [5]. A multi-module aquatic microplastic adsorption robot has been developed, incorporating a bionic gill filament system, microplastic adsorption materials, and fixed suction cups to achieve efficient capture of tiny microplastics, along with convenient recovery and detection. The performance of the robot was validated across marine, lacustrine, fluvial, and wastewater environments using SolidWorks Flow Simulation to model diverse complex aquatic conditions. This design integrates efficient adsorption, rapid recovery, and precise detection, filling a critical gap in the field of nanoscale microplastic detection. It provides robust technical support for the restoration of marine and freshwater ecosystems, thereby advancing Sustainable Development Goal 14 (Life Below Water).

2. Materials and methods

2.1. Bionic design principle

This study is based on the biological and hydrodynamic analysis of the filtration mechanism in sabellid worms [5, 6]. The radiolar crown structure of feather duster worms consists of radially arranged tentacles (gill filaments) on each side, adorned with pinnules (cilia). The gill filaments exhibit adaptive morphological curvature to accommodate water flow dynamics. Based on this mechanism, 3D printing flexible resin gill filament arrays is used to simulate gill filament dynamics in robot design; solid monolithic magnetic porous polymer material is used for the adsorption module to enhance chemical stability and selective adsorption capacity; and the shell was fabricated using 3D-printed Polylactic Acid (PLA), which has high corrosion resistance to complex water environments (no degradation in natural seawater for 52 weeks). The recyclability of raw materials, controllable degradability, and low-carbon manufacturing process of PLA align with the principles of environmental sustainability. At the same time, PLA cost is low, making it suitable for mass production.

2.2. Robot modeling

Robot modeling was performed using SolidWorks, encompassing the following sub-modules:

Formlabs Flexible 80A Resin integrates flexibility with mechanical robustness (Tensile strength at break: 7.2 MPa, elongation stress at 100%: 4.5MPa, elongation at break: 135%). This material can withstand repeated bending, flexing, and compression while demonstrating rapid shape recovery. Accordingly, photopolymerization 3D printing was employed to fabricate flexible resin (Formlabs Flexible 80A) gill filament arrays that accurately replicate both the flexibility and pinnate structure of featherworm gills. Each gill filament is equipped with branched, feather-like cilia distributed along its longitudinal axis. The total number of gill filaments is 16, arranged in a radially symmetric, feather-like configuration overall, emulating the radiolar crown structure and hierarchical filtration mechanism of fan worms. Polyvinylidene fluoride (PVDF) piezoelectric films (thickness: 20 μm; width: 3.14 mm; length: 1.3 mm; driving voltage: 2–4 V; vibration frequency: 10–30 Hz) are embedded within the cilia. During fluid flow, the primary gill filaments deflect at a certain angle with the current. The cilia on the filaments align with the current, forming a V-shaped angle with the stream, which generates a central vortex to selectively transport microparticles toward the adsorption module. Under static fluid conditions: The piezoelectric film vibrates, inducing coordinated wave-like motion in the cilia. This generates directional flow toward the adsorption block, thereby facilitating microparticle transport.

The biomimetic gill filaments are anchored at their base to a Polylactic Acid (PLA) tube with internal threads.

Transient maximum vibration velocity of cilia tip:

$$v_{max} = 2\pi f A \approx 2.51 mm/s \tag{1}$$

Stokes oscillation boundary layer thickness:

$$\delta = \sqrt{\frac{2\nu}{\omega}} = 146 \mu\text{m} \tag{2}$$

Reynolds numberRe:

$$Re = \frac{\rho v \delta}{\mu} \approx 0.37 \ll 1 \tag{3}$$

The maximum induced velocity of a single cilium is 2.51 mm/s.

2.2.1. Adsorption modules

The Fe_3O_4 acid-functionalized magnetic nanoparticles (Fe_3O_4@AC) synthesized by Ivanilson da Silva de Aquino's research group (particle size range: 20–200 μm; average nanoparticle diameter: 5 nm; specific surface area: 110 m^2/g; total pore volume: 0.21 cm^3/g; pore size range: 42–160 nm) were prepared using iron(III) chloride hexahydrate (Sigma Aldrich, Brasília, Brazil, 98%), citric acid (Sigma Aldrich, Brasília, Brazil, 99.5%), and iron(II) sulfate pentahydrate (Vetec, Brasília, Brazil, 99%) as the primary chemical reagents via an aqueous co-precipitation method. These nanoparticles, through mechanisms such as surface hydrogen bonding and van der Waals forces, achieved over 80% microplastic adsorption efficiency in 30 mL suspensions prepared with deionized water and 0.03 g of Microplastics (MPs) in a 1:1:1 ratio of HDPE, LDPE, and PP, under conditions of room temperature, pH 6, Fe_3O_4@AC nanoparticle concentration of 1.0 g/L, and a contact time of 30 minutes. Post-experiment, microplastic-loaded Fe_3O_4@AC nanoparticles were immersed in acetone and subjected to ultrasonic treatment (60 Hz) for 30 minutes. Subsequently, they were dried at 100°C for two hours and reused in adsorption experiments. After five cycles, the microplastic removal efficiency remained above 50% [7]. Meanwhile, to facilitate disassembly, the adsorbent material was fabricated in solid form in this study. Polydivinylbenzene (PDVB) exhibits high chemical stability and mechanical strength, and its pore structure and size distribution can be tuned by adjusting the crosslinking degree (20–50 mol% DVB). Thus, PDVB was selected as the matrix, embedding Fe_3O_4@AC nanoparticles to prepare a solid, monolithic, magnetic, porous polymer material (pore size: 1–100 μm, porosity: 70%) via microemulsion templating.

2.2.2. Suction cup for fixing

Chen's team designed a biomimetic suction cup inspired by the bream. Motor rotation drives the electromagnet away from the sealing edge, causing bidirectional movement of the actuator, which creates a negative pressure cavity enabling the suction cup to attach or detach [8]. This suction cup exhibits excellent underwater performance while being more compact than conventional vacuum-based models. The robot in this study employs this suction cup for secure attachment. Motor movement is synchronized with the housing's slider mechanism: during motor reversal, the suction cup detaches, allowing the slider's top section to protrude one unit above the housing, thereby facilitating the removal of bionic gill filaments and the suction pad. During motor forward rotation, the slider retracts into the channel, preventing accidental detachment of the bionic gill filaments and ensuring their stable fixation.

2.2.3. Shell

The housing is fabricated via Fused Deposition Modeling (FDM) 3D printing using Polylactic Acid (PLA), with dimensions of 100 mm × 40 mm × 75 mm and a wall thickness of 1 mm. Pre-designed cylindrical channels are integrated into the housing to facilitate water flow. Within these channels, a cylindrical tube slider is integrated and mechanically coupled to the motor motion. The outer circumference of the slider's top is equipped with external threads that mate with internal threads at the base of the biomimetic gill filaments. A central area is reserved for securing the adsorption module, while the remaining structural components are fastened to the housing via snap-fit connections, enabling convenient disassembly and maintenance. The outer surface of the housing is coated with a Polydimethylsiloxane (PDMS) waterproof layer (thickness: 10 μm; contact angle: 150°), using a spray coating process (spray pressure: 0.4 MPa; coating flow rate: 270 mL/min), thereby ensuring corrosion resistance, watertightness, and thermal stability.

The operational state diagram of the biomimetic robot designed based on the aforementioned principles is illustrated in Figure 1, while the cross-sectional views (front and left sections) are presented in Figure 2.

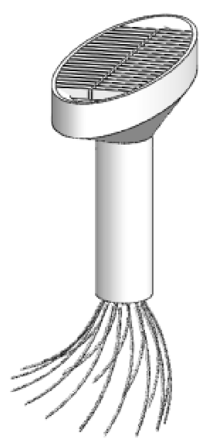

Figure 1. Working state diagram of robot

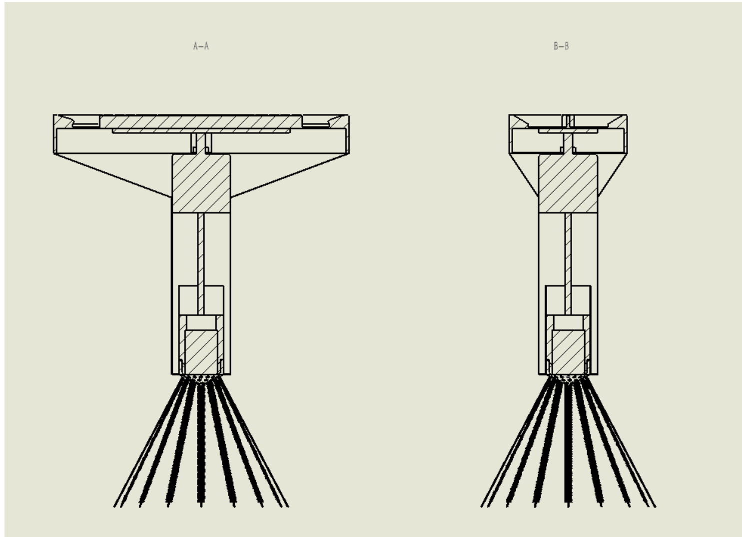

Figure 2. Robot section (Front section/Left section) (Some references to bionic suction cups [6] redrawn)

3. Simulation experiment design

Simulation experiments were conducted using SolidWorks Flow Simulation to replicate five aquatic environments with different flow velocities: 0.05 m/s, 0.07 m/s, 0.09 m/s, 0.2 m/s, and 0.5 m/s.

(1) Fluid Parameters: water (fluid), density ρ = 1000kg/m³, dynamic viscosity μ = 0.001Pa.s, temperature t = 293.2 k, turbulence intensity 0.1%.

(2) Grid settings and run settings: using SolidWorks automatic grid setting, initial grid level 3, minimum gap size 0.0001m. The incoming flow direction is the x axis, and the incoming flow size is 0. 05m/s, 0.07m/s, 0.09m/s, 0.2m/s, 0.5m/s. The number of iterations is 100.

(3) Simulation results: As illustrated in Figure 3, when the flow velocity is below 0.09 m/s (a)(b), the water flow induces ciliary vibration, generating a weak shear flow that dominates microplastic transport. The active wave-induced modulation of the gill filament array enhances the convective flux of microplastics toward the adsorption surface. With increasing flow velocity, the collision frequency between microplastics and the adsorption surface increases linearly, resulting in a continuous improvement in adsorption efficiency. When the flow rate reaches at 0.09m/s (c), the shear flow and diffusion are the best, the particle residence time is optimal, and the adsorption efficiency peaks. When the flow velocity is greater than 0.09 m/s (c). As the flow velocity increases further, the high shear force induces desorption of adsorbed microplastics, while the insufficient residence time of the particles reduces the probability of effective collisions, leading to a rapid decline in adsorption efficiency until the adsorption capacity is completely compromised under high-speed flushing (e).

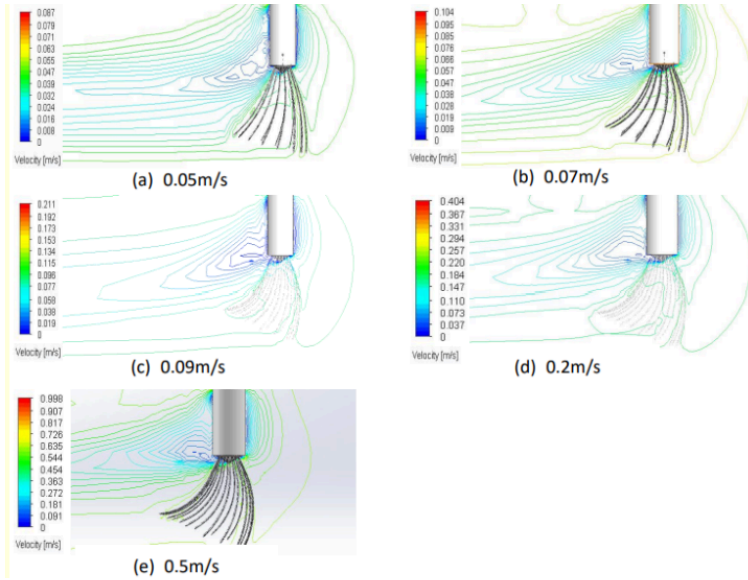

Figure 3. Fluid simulation velocity isogtam (Panels (a)~(e) in the figure represent the flow velocities: 0.05m/s, 0.07m/s, 0.09m/s, 0.2m/s, 0.5m/s; The color bar indicates the velocity magnitude.)

4. Conclusion

The proposed biomimetic microplastic-adsorbing robot exhibits high efficiency and precision across diverse aquatic environments, including slow-flowing rivers, calm marine areas, lakes, and wastewater systems, for the detection of microplastics. It achieves efficient adsorption and capture of sub-100 μm microplastics. Following collection, the adsorption module enables rapid desorption and detachment for convenient onshore analysis and detection. In the case of biomimetic gill filament damage, rapid replacement is feasible. Furthermore, the robot features a cost-effective design: its core components are fabricated using SLA 3D printing with Formlabs Flexible 80A Resin, and the PVDF membrane is driven by low-voltage actuation, ensuring low energy consumption. The total manufacturing cost is lower than that of conventional trawl or pump-based sampling techniques. Moreover, the integration of biocompatible materials and scalable printing technologies renders large-scale production of the robot feasible. Nevertheless, the current robotic system still has inherent limitations: the bionic gill filament design has intrinsic deficiencies that hinder the achievement of maximum adsorption efficiency. Owing to size constraints of these filaments, the robot experiences functional failure under high-velocity flow conditions. The limited maximum adsorption capacity restricts long-term operational performance. Robotic components undergo excessive wear during operation in highly corrosive liquids, such as seawater. This necessitates the removal of adsorption modules for shore-based inspection, as autonomous in-situ detection remains unfeasible. Future research should prioritize optimizing the bionic gill filament structure to improve adsorption efficiency. Adsorption modules fabricated from alternative materials should be developed to enable the capture of other types of microparticles. Novel corrosion-resistant materials or coatings should be investigated to extend the operational lifespan of the robot in harsh environments. Incorporating sensing modules is advisable to enable in situ self-detection capabilities. Furthermore, integrating an underwater propulsion system will enable autonomous navigation, facilitating the assessment of microplastic concentrations at different water column depths.

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