

An Adaptive Bioinspired Microfluidic Robot: Design and Performance Evaluation for High-Viscosity Fluid Delivery

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Abstract. Microscale transportation and delivery of high-viscosity fluids have long posed major technical hurdles for biomedical detection, pharmaceutical preparation and chemical analysis work. Traditional micropump devices show obvious deficiencies when handling viscous fluids, including low working efficiency, excessive energy consumption and poor adaptability to fluids with varying physical properties. To tackle the above problems, this work draws inspiration from the feeding structure of rhinoceros beetles and adopts asymmetric capillary structures to realize efficient extraction of high-viscosity fluids from plant tissues. A new type of microfluidic delivery robot designed based on bionic principles is proposed in this paper. The robot is assembled with three key functional units: the passive microfluidic diode structure that enables one-way fluid movement without movable parts, the electromagnetic active driving module that realizes precise flow regulation, as well as multi-type sensors matched with closed-loop control algorithms to adapt to fluids with complex characteristics. Relevant experimental results prove that the transportation efficiency of this new device is 50% higher than that of traditional peristaltic micropumps. Meanwhile, it can work stably even when fluid viscosity changes by a hundred times. The robot has been successfully applied in fields such as pharmaceutical delivery, high-viscosity fluid chemical synthesis and environmental sample testing. This research effectively combines bionics technology with microfluidic engineering, and provides a reliable, adaptable technical solution for the next-generation fluid control equipment.

Keywords: Bioinspired microfluidics, Microfluidic transport robot, Electromagnetic actuation, High-viscosity fluid transport, Microfluidic diode

1. Introduction

Accurate control and transmission of tiny-volume fluids serve as the technical foundation for modern biomedical testing, pharmaceutical research and microscale chemical synthesis [1]. In actual application scenarios, researchers often need to process high-viscosity fluids, which are widely used in biological sample analysis and polymer material research. However, mainstream microfluidic equipment at present, including mechanical peristaltic micropumps and passive capillary devices, cannot work well when dealing with such fluids [2]. The core difficulties of this research lie in two aspects. On the one hand, it is necessary to realize low-energy fluid delivery in narrow

microchannels. On the other hand, the equipment should maintain adjustable performance when facing fluids with different properties. Devices that rely purely on capillary force can save energy, yet they fail to actively adjust fluid flow states. Mechanical active pumps can control flow rates flexibly, but they consume large amounts of power, suffer from component wear easily, and their working performance will drop sharply when transporting viscous fluids [3]. There has always been a balance problem between operating efficiency and control capability in existing equipment. Against this background, it is urgent to develop innovative microfluidic structures that integrate the strengths of different technical routes.

Natural organisms have evolved mature solutions to similar fluid transportation problems. Rhinoceros beetles, which belong to the Dynastinae subfamily, rely on their special mouthparts to suck high-viscosity tree sap. These mouthparts are equipped with asymmetric capillary structures, and the surface wettability of different areas is different. With such structures, the beetles can complete one-way fluid transmission without consuming extra energy [4, 5]. Referring to this biological structure and working mechanism, this paper develops a bionic microfluidic delivery robot. The equipment integrates three core technologies: first, the passive microfluidic diode array. It uses asymmetric channel structures and modified surface characteristics to guide fluids to flow in a single direction. Second, the electromagnetic active driving module, which can adjust fluid flow rates dynamically. Third, multi-type sensors and closed-loop control algorithms, which help the device respond in real time to fluids with complex physical properties [6]. A series of tests show that compared with traditional peristaltic micropumps, the transportation efficiency of the proposed robot increases by 50%, and it can operate normally when fluid viscosity fluctuates by a hundred times. This study connects bionic research and microfluidic engineering, and provides a stable and adaptable equipment option for precision medical treatment, chemical synthesis and environmental monitoring that require microfluidic control.

2. Bioinspired design principles from rhinoceros beetles

Rhinoceros beetles take in high-viscosity tree sap through their mouthparts, and the whole fluid transmission process is one-way and does not need external power supply. The working mechanism depends on two key factors, namely asymmetric capillary structures and surface areas with gradient wettability [7, 8]. According to the Young-Laplace equation, the capillary pressure difference formed on the curved liquid surface is related to the local contact angle and channel structure. For this reason, the surface wettability gradient will generate directional driving pressure, and fluids will flow from hydrophobic areas to hydrophilic areas. Inside the sap absorption channel of rhinoceros beetles, this mechanism forms a stable one-way flow. Fluids can move forward with little resistance, while reverse flow will be blocked due to sudden structural changes and unfavorable surface wetting conditions [4, 5]. This pure passive one-way pumping mode can automatically adapt to sap with different viscosity and surface tension, which is a high-efficiency and stable fluid transmission strategy formed through biological evolution.

This study extracts three practical engineering design rules from the fluid transmission structure of rhinoceros beetles, and apply them to the development of the microfluidic delivery robot. Firstly, design asymmetric channel structures. The channel expands gradually along the forward flow direction and shrinks sharply in the reverse direction. Such a structure leads to obvious differences in fluid resistance in two directions, thus forming a passive diode structure. Secondly, carry out regional modification on the channel surface to build a wettability gradient. This design can further strengthen the one-way flow effect by controlling the moving state of liquids at key positions. Thirdly, considering that pure passive structures cannot meet the active regulation needs of practical

microfluidic experiments, this study combines the passive diode structure with electromagnetic driving components. The combined structure not only ensures low-energy one-way fluid delivery, but also realizes programmable flow regulation [6]. Based on the above design rules, the overall structure and specific implementation scheme of the bionic equipment are elaborated in the third section.

3. System design and implementation

3.1. System architecture and material realization

The bionic microfluidic delivery robot is composed of four mutually matched functional modules: the microfluidic diode array (MDA) for passive one-way flow control, the electromagnetic actuation module (EAM) for active flow adjustment, the integrated sensor group (ISS) for multi-parameter real-time monitoring, and the adaptive closed-loop control module (ACCM) for dynamic parameter adjustment. To simulate the asymmetric wettability characteristics of rhinoceros beetles' sap absorption channels, polydimethylsiloxane (PDMS) is selected as the main production material. This material features good light transmittance, stable chemical properties and is compatible with soft lithography processing technology. This study adopt two methods to modify the channel surface in different regions: oxygen plasma treatment is used to form hydrophilic areas, and perfluorodecyltrichlorosilane (PFDS) vapor deposition is adopted to build hydrophobic areas. After modification, the contact angle of the channel surface ranges from about 25° to 155°, which is consistent with the wettability characteristics of the biological prototype [9, 10].

3.2. Passive microfluidic diode design

The microfluidic diode relies on the combination of asymmetric channel structures and artificially constructed wettability gradients to realize one-way flow control. When fluids flow forward, the channel presents a conical shape with gradual expansion, so the flow resistance is relatively low. In the reverse flow direction, the channel diameter suddenly changes from 200 μm to 50 μm. Sudden structural contraction will cause flow separation and form capillary barriers, resulting in great flow resistance [11]. This study applies hydrophobic coating at the contraction position of the channel. The coating can fix the liquid interface effectively and further prevent reverse flow. We use the diode index to quantify the difference of fluid pressure in forward and reverse directions, and the calculation formula is as follows:

$$D_{\text{index}} = \frac{\Delta P_{\text{rev}}}{\Delta P_{\text{fwd}}} \quad (1)$$

Under conventional working conditions, the diode index of the structure is between 8 and 12. This data proves that the device has excellent one-way flow control capability. Even without movable parts, it can still complete the stable transmission of high-viscosity fluids [8, 12].

3.3. Active actuation and closed-loop control

The active regulation of fluid flow is realized by a diaphragm driven by an electromagnetic coil. The diaphragm is made of PDMS composite film mixed with NdFeB magnetic particles. By changing the current of the coil, this study adjusts the electromagnetic driving force, so as to control the single stroke displacement and working frequency of the diaphragm in a programmed manner [6, 13]. The

volumetric flow rate of fluids is determined by three factors: the effective area of the film, the working frequency and the displacement volume of each stroke. According to this rule, this study adjusts the flow state dynamically. Micro-electromechanical system (MEMS) pressure sensors and thermal flow sensors are installed inside the microchannel to monitor the real-time hydraulic parameters. Meanwhile, ion-sensitive field-effect transistor (ISFET) pH sensors are equipped to expand the application scope of the device in biochemical research. All data collected by sensors are transmitted to a proportional integral derivative (PID) controller optimized by fuzzy logic algorithms. When the sensor detects changes in fluid viscosity, the controller will adjust the driving current in a timely manner. Specifically, the fuzzy logic unit modifies the PID parameters according to the deviation value and change rate of flow data. Even if fluid properties change abruptly, the equipment can maintain stable operation.

This design combining passive structures and active feedback control has a flow control accuracy of $\pm 5\%$, and the response time is less than 200 ms. This study carries out tests with fluids whose viscosity changes by a hundred times. The results show that the closed-loop control system works well. Even when transporting high-viscosity non-Newtonian fluids, the fluctuation range of flow rate is only $\pm 8.5\%$ [6, 14]. The organic combination of passive one-way flow structures and active feedback control is the biggest difference between this robot and traditional micropumps.

4. Experimental performance evaluation

4.1. Experimental design and benchmark

Table 1 lists the detailed information of the experimental platform, test fluids and comparison equipment. The experiment aims to test several core performance indicators of the bionic microfluidic robot, including fluid transportation efficiency, adaptability to different viscosity fluids and the capacity of handling non-Newtonian fluids. To make the comparison results more convincing, this study selects three widely used microfluidic driving devices as the reference groups, namely traditional mechanical peristaltic micropumps, pure passive capillary equipment and electrowetting-on-dielectric (EWOD) digital microfluidic devices. All experiments are completed under fixed environmental conditions: the ambient temperature is controlled at $23 \pm 1^\circ\text{C}$, and the relative humidity is maintained at $50 \pm 5\%$. Such settings can reduce the influence of temperature on fluid viscosity and the dimensional change of PDMS materials, and ensure that all comparative test results are repeatable.

Table 1. Summary of experimental setup

Category	Details
Test platform	Soft lithography fabricated PDMSbased microfluidic robot Flipchip integrated electromagnetic actuators Multimodal sensors
Test Fluids	Deionized water Glycerin solutions (500-1000 mPa·s) Shearthinning CMC nonNewtonian fluids (flow behavior index $n = 0.8$) Crude oil (100-50,000 mPa·s, wide viscosity range sample)
Benchmark Systems	Conventional peristaltic micropump (mechanical) Passive capillary-only system (no active control) Electrowetting-on-dielectric (EWOD) digital microfluidic platform

Table 1. (continued)

Key Evaluation Metrics	Transport efficiency Viscosity adaptability Non-newtonian fluids
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4.2. Core performance results

Table 2 compares the core performance data of the proposed bionic robot and three types of reference equipment. The test results verify that the new robot has higher working efficiency, faster response speed and better stability when transporting high-viscosity fluids and non-Newtonian fluids.

Table 2. Performance comparison of different microfluidic systems

Index	Proposed Bioinspired Robot	Peristaltic Micropump	Passive Capillary System	EWOD Platform
Transport efficiency	72%	48%	65%	58%
Response time	150–200 ms	500–1000 ms	N/A	N/A
Flow stability (non-newtonian CMC)	$\pm 12\%$	$\pm 40\text{--}50\%$	N/A	N/A
Viscosity adaptability	10–50,000 mPa·s	N/A	N/A	≤ 200 mPa·s
Flow-rate variation (10-1000 mPa·s)	$\pm 8.5\%$	$\pm 35\text{--}40\%$	N/A	$\pm 30\%$ (>200 mPa·s)

4.2.1. Transport efficiency

In this experiment, this study defines transportation efficiency as the ratio of output hydraulic power to input electric power. Under the standard test conditions where the flow rate is 10 $\mu\text{L}/\text{min}$ and the test fluid is 500 mPa·s glycerin solution, the transportation efficiency of the bionic robot reaches 72%, and the response time is between 150 ms and 200 ms. By contrast, the efficiency of peristaltic micropumps is only 48%, with a response time ranging from 500 ms to 1000 ms. The efficiency of pure passive capillary equipment is 65%, but it cannot realize active flow regulation. The efficiency of EWOD equipment is 58%, and it can only be used for low-viscosity fluid transmission. Compared with traditional peristaltic micropumps, the transportation efficiency of the new robot is increased by 50%. This advantage comes from the low-loss passive diode structure and the high energy conversion efficiency of electromagnetic driving components [13].

4.2.2. Viscosity adaptability

This study selects fluids with viscosity ranging from 10 mPa·s to 1000 mPa·s to test the equipment's ability to maintain stable flow under different viscosity conditions. When the closed-loop control system is turned on, the flow rate fluctuation of the bionic robot is only $\pm 8.5\%$. For peristaltic micropumps, mechanical sliding and pressure saturation will occur during operation, leading to a flow rate fluctuation of $\pm 35\%$ to $\pm 40\%$. When the fluid viscosity exceeds 200 mPa·s, the flow deviation of EWOD equipment reaches $\pm 30\%$. The excellent viscosity adaptability of the robot is derived from its dual working mode. The asymmetric diode structure can adapt to the pressure

change caused by fluid viscosity variation, and the PID controller optimized by fuzzy logic can offset the residual flow disturbance through active regulation [6].

4.2.3. Handling of non-Newtonian fluids

This study adopt shear-thinning carboxymethyl cellulose (CMC) solution with a flow behavior index of 0.8 as the non-Newtonian test fluid, and set the shear rate between 1 s^{-1} and 100 s^{-1} . The test results show that the flow rate fluctuation of the bionic robot is controlled within $\pm 12\%$. Under the same experimental conditions, the flow rate of peristaltic micropumps fluctuates by $\pm 40\%$ to $\pm 50\%$. The real-time data feedback of the sensor group enables the robot to adjust the electromagnetic driving state continuously, so as to compensate for the viscosity change of fluids caused by different shear rates [14]. This performance advantage proves that the equipment equipped with sensing and adaptive control modules can cope well with the viscosity change of non-Newtonian fluids in different shear states, and is suitable for processing various actual biological and chemical fluids.

4.3. Application verification

This study selects three typical application scenarios to verify the comprehensive performance of the bionic microfluidic robot. Table 3 compares the working effects of the robot and traditional processing methods in each scenario. It can be seen that the new robot has obvious advantages in positioning accuracy, product synthesis quality and sample analysis efficiency.

Table 3. Performance comparison in application verification

Application Domain	Performance Metric	Conventional Method	Proposed Robot	Improvement
Biomedical drug delivery	Positional accuracy (μm)	± 200 (passive diffusion)	± 50	$\sim 4\times$ better accuracy
High-viscosity chemical synthesis (200-800 $\text{mPa}\cdot\text{s}$)	Product yield increase	Baseline (manual batch)	Baseline+ 15-25%	+15-25%
	Purity improvement	Baseline (manual batch)	Baseline+ 8-12%	+8-12%
Environmental sample analysis (100-50,000 $\text{mPa}\cdot\text{s}$ crude oil)	Analysis time (min/sample)	30–40	<5	6-8 $\times$ reduction

In the field of biomedical drug delivery, the robot can accurately control magnetic nanoparticle carriers to move in microchannels. The positioning error of the target delivery position is within $\pm 50 \mu\text{m}$, while the positioning accuracy of the traditional passive diffusion delivery mode is only $\pm 200 \mu\text{m}$ [13]. The fourfold improvement in positioning accuracy makes the robot applicable to targeted drug delivery scenarios with high spatial precision requirements.

In the synthesis experiment of high-viscosity chemical products, the robot can realize automatic proportioning of polymer reactants with viscosity between 200 $\text{mPa}\cdot\text{s}$ and 800 $\text{mPa}\cdot\text{s}$. Compared with the traditional manual batching method, the product yield increases by 15% to 25%, and the product purity is improved by 8% to 12%. This is because the automatic fluid control mode optimizes the mixing effect of raw materials and realizes more accurate proportion control of reactants [11].

In the environmental sample analysis test, this study takes crude oil samples with viscosity from 100 $\text{mPa}\cdot\text{s}$ to 50000 $\text{mPa}\cdot\text{s}$ as test objects. The robot can complete the viscosity classification of

each sample within 5 minutes. Traditional analytical methods need 30 to 40 minutes to process a single sample, and the analysis efficiency is greatly improved [14]. The above application tests fully prove that the robot can work stably in pharmaceutical, chemical and environmental monitoring fields..

5. Conclusion

Aiming at the difficulty of efficient and adaptive transmission of high-viscosity microscale fluids, this paper develops a bionic microfluidic delivery robot. The core innovation of the research lies in the combined design of two sets of structures: one is the passive microfluidic diode. It draws on the feeding characteristics of rhinoceros beetles, and uses asymmetric channel structures and gradient surface wettability to realize one-way fluid flow. The other is the active electromagnetic driving unit matched with fuzzy logic optimized closed-loop control system. This combined design breaks the bottleneck of traditional equipment that cannot balance working efficiency and control performance. The transportation efficiency of the robot is 50% higher than that of peristaltic micropumps, and when fluid viscosity changes by a hundred times, the flow rate fluctuation is still controlled within $\pm 8.5\%$.

To sum up, the proposed robot is a new type of microfluidic control equipment integrating passive one-way flow, programmable active flow regulation and real-time adaptive sensing functions. It performs well in nanoparticle drug delivery, high-viscosity polymer synthesis and crude oil sample analysis, and has wide application prospects in biomedicine, chemical industry and environmental monitoring. At present, the equipment still has some limitations: it can only process single-phase fluids normally, the applicable temperature range is narrow, and the maximum processing flow rate is less than 100 $\mu\text{L}/\text{min}$. In follow-up research, this study will explore control algorithms based on neural networks to realize the processing of complex multi-component fluids, optimize the structural design to increase the overall throughput, and continue to learn from other biological fluid transmission structures to develop more excellent microfluidic equipment.

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