Flow Tweezing of Anisotropic Magnetic Microrobots in a Dynamic Magnetic Trap for Active Retention and Localized Flow Sensing

Yuan Liu
Shenzhen Institutes of Advanced Technology

Quanliang Cao
Huazhong University of Science and Technology

Haifeng Xu
Shenzhen Institutes of Advanced Technology

Gungun Lin
gungun.lin@uts.edu.au

University of Technology Sydney

Research Article

Keywords:

Posted Date: May 24th, 2024

DOI: https://doi.org/10.21203/rs.3.rs-4173218/v2

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: The authors declare no competing interests.
Flow Tweezing of Anisotropic Magnetic Microrobots in a Dynamic Magnetic Trap for Active Retention and Localized Flow Sensing

Yuan Liu,* Quanliang Cao,2,3 Haifeng Xu1, and Gungun Lin4*

1Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences, Shenzhen, Guangdong Province, P. R. China, 1068 Xueyuan Avenue, Shenzhen 518055, China
2Wuhan National High Magnetic Field Center, Huazhong University of Science and Technology, Wuhan, 430074, China
3State Key Laboratory of Advanced Electromagnetic Technology, Huazhong University of Science and Technology, Wuhan, 430074, China
4Institute for Biomedical Materials and Devices, School of Mathematical and Physical Sciences, Faculty of Science, University of Technology Sydney, 15 Broadway, Ultimo, NSW 2007, Australia

Abstract: Controlled manipulation of microscale robotic devices in complex fluidic networks is critical for various applications in biomedical endovascular sensing, lab-on-chip biochemical assays, and environmental monitoring. However, achieving controlled transport and active retention of microscale robots with flow sensing capability have proven challenging. Here, we report the dynamic tweezing of an anisotropic magnetic microrobot in a rotating magnetic trap for active retention and localized flow sensing under confined fluidic conditions. We reveal a series of unconventional motion modes and dynamics of the microrobot transporting in a confined fluidic flow, which manifest themselves as transitions from on-trap centre rolling to large-area revolution and off-trap centre rolling with varying rotating frequencies. By retaining the robot within the magnetic trap and its motion modulated by the field frequency, the off-centre rolling of the microrobot endows a crucial localized flow sensing capabilities, including flow rate and flow direction determination. The magnetic microrobot serves as a mobile platform for measuring the flow profile along a curved channel, mimicking a blood vessel. Our findings unlock a new strategy to determine local magnetic tweezing force profile and flow conditions in arbitrary fluid channels, revealing strong potential for microfluidics, chemical reactors, and in-vivo endovascular flow measurement.

Introduction

Controlled transport of microscale functional systems in fluidic flows has key applications in lab-on-chip microfluidic devices,12 chemical reactors,34 and in-vivo physiological systems featuring hierarchical networks of capillaries, arteries and veins.5-7 Traditional wired devices (e.g., differential pressure flowmeter and cantilever-based flowmeter) face difficulties in their manipulation in small and confined spaces.8910 Magnetically responsive microrobots with programmed shape and anisotropy have shown significant potential due to their miniaturised fingerprints and untethered manipulation capability.1112 Equipped with motion capabilities, such systems function as mobile platforms for applications, including localized sensing,1314 drug delivery,1516 and cargo transport.1718 However, most of the existing systems focus on locomotion in static fluids.1920 The efficient control and transport of the systems in dynamic fluidic flows remain elusive.2112

Magnetic tweezers possess the trapping capability to physically confine a magnetically responsive object in fluids.22 They are widely established by using a pair of permanent magnets,23 a single magnet,24 or a cylindrical magnet.22 The trapping magnetic fields of tweezers feature a local maximum of field strength to trap magnetic particles.25 It has been reported that a rotating magnetic field can drive magnetic structures of various morphologies (e.g., magnetic microsphere26,27 and dimer-shaped microstructures28,29) into synchronous rotation at low frequencies and further to large-area revolution at high frequencies in unconfined fluids. The magnetic field control strategy enables the localization
and retention of magnetically powered devices in the lumens (e.g., intestine\textsuperscript{30} and blood vessels\textsuperscript{12}) of the human body. Flow in the lumens generates the propelling force to prevent retention. Localized flow sensing provides valuable feedback on flow conditions, facilitating the optimization of magnetic field parameters to enhance device retention. However, achieving effective localized flow sensing poses a significant challenge for mobile microrobots in confined fluidic flows.

Here, we report the dynamic magnetic field tweezing of microrobots for active device retention and localized flow sensing (Fig. 1). The coupling between the magnetic trapping field, confined fluidic flow field and the microrobotic body, results in intriguing in-flow locomotion characteristics. Switchable motion modes are proposed, achieved by balancing the magnetic force and the flow force. The magnetic robot can switch its locomotion mode from “on-trap centre rolling” to “large-area revolution” with varying rotating magnetic field frequency. The revolution of the particle can be further modulated from “on-trap centre rolling” to “off-trap centre rolling” at varied flow speeds. These motion modes imbue the microrobot with multiple functions. Dynamic magnetic tweezing provides the necessary magnetic force to retain the robot, and off-trap centre rolling enables localized flow sensing. On the trap center, the motion range of the microrobot can be controlled by adjusting the rolling frequency. Leveraging this manipulation strategy for microrobots using a dynamic rotating magnetic trap shows promise in various applications, including lab-on-chip microfluidic systems, micro-robotic control, and endovascular flow measurements.

**Figure.1** Tweezing a magnetic microrobot for in-flow sensing. (a) Schematic illustration of the experimental scenario. (i) Photo of a flow channel laden with a magnetic microrobot. (ii) Image of an anisotropic magnetic particle fabricated by photolithography. (b) Distributions of magnetic field and magnetic force. Inserted curves (coloured red) are the profile of the Y-axis components of the magnetic field gradient and magnetic force, respectively. (c) Conceptual illustration of the transition of a microrobot in an endovascular system-mimicking flow channel, which exhibits various locomotion modes, including on-trapping centre rolling, large-area revolution, and off-trapping centre rolling.

**Locomotion transition between on-centre rolling and revolution**
We fabricated the magnetic microrobots by lining up magnetic nanoparticles embedded in a polymer matrix. The microrobot structure was fabricated utilizing a magnetic field-assisted photolithography approach, as illustrated in Fig. 1a. In brief, this methodology involved the application of a magnetic field to guide the assembly of superparamagnetic nanoparticles (7 wt%) through short-range dipolar interactions in the PEG-DA hydrogel, thereby establishing magnetic anisotropy axis, commonly referred to the chaining direction of nanoparticles, in alignment with the direction determined by the applied magnetic field. The shape of the robotic body was defined through computer-aided design, specifying geometry features on a photomask. The dimensions of the resulting robots ranged from dozens of microns to millimetres. For the tweezing study, we used a pair of permanent magnets, each with a diameter of 3 cm and positioned 5 mm apart to produce the desired magnetic field patterns. COMSOL simulations were conducted to ascertain the magnetic field distribution, revealing that the in-plane component, $B_y$, exhibited a local maximum field strength at the field centre, measured at 50 mT (Fig. 1b), which enables trapping the microrobot toward the field centre.

Figure.2 Locomotion transition between on-centre rolling and revolution based on cycling field. (a) Schematic of transition between on-centre rolling and large-area revolution under the modulation of centrifugal force. (b) Forces exerted on the magnetic microrobot, including magnetic centripetal force, rolling force and centrifugal force. (c) Motion dynamics of the magnetic microrobot at varying magnetic field frequencies. $d_1 \approx 2.5$ mm, and $d_2 \approx 4$ mm. Colored dots indicate the motion trajectories of the microrobot.

To instigate the locomotion in confined fluidic flow, we injected a microrobot in a flow channel with a 2 mm inner diameter at the magnetic field (B) centre of the magnets. One side of the flow channel was connected with a fluidic pump for liquid injection (0~100 µL/s). It was shown that the microrobot exhibited two primary motion modes as illustrated in Figure 2a. The microrobot was trapped at the centre of the rotating magnetic field and rotating under a low-frequency magnetic field. At zero flow rates, the microrobot experiences a magnetic centripetal force, a rolling friction force, and a centrifugal force (Fig. 2b). The magnetic (centripetal) force scales within 1 cm-distance away from the magnetic field centre and its value at the field centre is zero. With the increasing rotation rate of the field, the increasing centrifugal force pushes the microrobot off the centre position, leading to the swing of the microrobot around the symmetry centre of the field. For instance, the microrobot measured with a dimension of 400 µm *600 µm *150 µm
can rotate around its centre at low frequencies of 0~1000 rpm. When the frequency increases to 1000 rpm, the microrobot experiences a centrifugal force of over 4.52 nN (\(F_c = mrw^2\), in which \(m\) is weight, \(r\) is the off-axis radius, and \(w\) is angular speed). This force can overcome the magnetic force and rolling friction force, leading to the microrobot to swing off the centre with modulated trajectory ranges (~2.5 mm for 1100 rpm and ~4 mm for 1500 rpm) (Fig. 2c and Movie S1). When the microrobot does the revolution locomotion, the trajectory is elliptical rather than circular due to space limitations. The rolling magnetic field with an established magnetic potential well facilitates the trapping of magnetic microrobot within the confined channel. By adjusting the rolling frequency, the motion modes can be dynamically switched from on-trapping centre to large-scale revolution.

**Active retention and fluidic sensing of magnetic microrobots**

To investigate the influence of fluidic flow, we monitor the motion dynamics of microrobots at varying flow rates with and without magnetic fields. Figure 3a shows that without applying a rotating magnetic field, a statically trapped microrobot was suddenly washed off from the centre at a higher flow rate of 80 \(\mu\)L/s when the flow rate is gradually increased from 0. The fluidic drag force is expressed as:

\[ F_d = \frac{1}{2} \rho v^2 C_D A \]

where \(\rho\) is the density of the fluid, and \(v\) is the speed. \(A\) is the cross-section area, and \(C_D\) is the drag coefficient. At the low \(Re\) (i.e. close to 1 for flow rate varying from 0 to 50 \(\mu\)L/s (0~16 mm/s)), the drag coefficient is asymptotically proportional to \(Re^{-1}\):

\[ C_D \sim Re^{-1} = \frac{\mu}{\rho v D} \]

Thus, the fluidic drag force is directly modulated by the flow speed as \(F_d \propto v\). Based on the fluidic drag force, the static frictional force is estimated as high as 70 nN.

When the microrobot is set to roll, the fluidic drag force pushes the microrobot away from the centre until an equilibrium position is achieved, as shown in Figure 3a. The microrobot structure with a 200-rpm rolling speed at the field centre experiences a centrifugal force of up to 0.2 nN. To propel the microrobot away from the centre, 4.52 nN force is needed. A flow rate of 5 \(\mu\)L/s generates a drag force of about 4.32 nN to push the microrobot to a new position that is 0.55 mm distance away from the centre. In this respect, the off-centre distance was observed to scale with the flow speed (\(d\sim v\)). Importantly, such a scaling relationship between the fluidic drag and off-centre distance of a microrobot only holds when the particle is set to roll, which is absent for a static unrolling particle.

We demonstrated four major modes of motion with respect to varying flow rates and rotating field frequencies, which include “on-centre rolling”, “off-centre rolling”, “large-area revolution” and “flown off” (Fig. 3b, Fig. 3c, and Movie S2). At zero rotating field, the microrobot is either trapped at the centre or being flown off. With a rotating magnetic field, the microrobot rolls in the centre of the magnetic potential well and may undergo a “large-area revolution”. The microrobot with 1500-rpm speed switches from “large-area revolution” to “off-centre rolling” at the flow of 30 \(\mu\)L/s. In a confined fluidic flow field, the microrobot exhibits a dynamic form of “off-centre rolling” at the flow rate range of 5~62 \(\mu\)L/s at the 400-rpm rolling speed. When the drag force overcomes the magnetic force and the frictional force, the microrobot is washed off at the flow rate of 62 \(\mu\)L/s. We further found that a higher rotating speed leads to a smaller off-centre distance and renders a smaller magnetic force exerted on the microrobot, as the magnetic force scales with the off-centre distance (\(F_m \sim d\sim v\)). For example, the microrobot with a 200-rpm rotation speed travelled 6.5 mm at a flow rate of 40 \(\mu\)L/s, while it only travelled 3.5 mm in distance at a rotation speed of 800 rpm. As the magnetic force is reduced, a small flow speed is sufficient to transit the particle from an “off-centre rolling” state to a “flown off” state. The transition speed for 200 rpm is about 62 \(\mu\)L/s, while the transition speed for 800 rpm reduces to 48 \(\mu\)L/s. The scaling relationship between the microrobot’s off-centre distance and the flow speed equips the microrobot a flow-sensing capability, the range of which can be modulated by the rotation frequency of the magnetic field. Therefore, the magnetic
A microrobot can be retained in the confined channel at a rate of 55 μL/s, and a flow sensing range of 5~55 μL/s at the 400-rpm rolling speed. The switchable motion modes endow the microrobot with multiple functions, including retention-based trap centre rolling, large-area motion based on revolution, and flow sensing based on off-trap centre rolling.

![Figure 3](image)

**Figure 3** Tweezing of magnetic microrobot in a confined fluidic flow. (a) Motion modes under the static and cycling field (rolling field:600 rpm). (b) Influence of fluidic flow on the motion trajectory of the magnetic microrobot at 1500-rpm rolling speed. (c) Mapping of the motion modes of a microrobot regarding the variation of the rotation field frequency and the flow speed.

### Directional movement under the magnetic tweezer

The rolling of the microrobot generates propulsion through solid-liquid interaction, which allows us to explore the upstream motion capability of microrobots under dynamic magnetic tweezerling. Figure 4 shows that the dynamic magnetic trap may serve as a driving source for the in-flow directional movement of microrobot (Movie S3). The microrobot was observed to propel upstream, and the motion distance scales with the rotation speed from 200 rpm to 800 rpm (Figure 4a). The microrobot walked 2.24 mm at 1000-rpm rolling speed and the propelling force can reach 25.51 nN at 1000-rpm rotation frequency (0 μL/s flow speed, Figure 4b). This result shows the propelling force can be dynamically modulated by altering the field frequency. To further confirm the origin of the propelling force, we exchanged the flow direction and found that the propelling force exhibits a directional bias towards the right and is independent on the flow direction (defined in Fig. 4c, d). This suggests that the origin of the propelling force could be stemming from a non-reciprocal “rolling-walking”-like movement of the microrobot. Indeed, when the directions of the fluidic flow and propelling force align or opposes, the propelling force may augment or attenuates the flow effect, resulting in longer/shorter displacement distances towards the field centre, respectively (Fig. 4e). Our results (Figure 4f and 4g) further show that the relative directions between the flow drag force and propelling force could be leveraged to acquire a large flow responsive range. The maximum flow rate is 61.9 μL/s with a 7.8-mm distance (200 rpm distance) for flow from the right to left. The microrobot can respond to the flow direction, thereby functioning as a vector flow sensor for measuring both flow rate and direction.
**Figure 4** Directional movement of a microrobot in a dynamic magnetic trap. (a) Micrograph showing the directional motion of a microrobot at varying rotating field frequencies in static fluid. (b) Off-centre distance of a microrobot as a function of the rotation frequency of magnetic fields at zero flow rates. (c)-(d) Micrograph showing a microrobot at varying rotating field frequencies in different fluid flow directions. (e) Off-centre distance of the microrobot as a function of the rotation field frequency for different fluid flow directions. R to L: right to left; L to R: left to right. (f) Maximum flow rate to flush away the microrobot and (g) the maximum off-centre distance of the microrobot for different flow directions.

**Flow profile measurement with microrobots in a curved flow channel**

We further utilise the off-centre rolling phenomenon for flow sensing within a confined flow channel. Given the dynamic changes in the flow conditions typical of natural cavities in the human body, we replicated a blood vessel environment using a curved flow channel fabricated through high-temperature treatment (Figure 3A). The curved channel features a relatively smaller channel diameter of 1.5 mm. The microrobot structures can be transported and trapped at the corner of the curved channel. By varying the speed and recording the points of transition from off-centre rolling to flowing outside, we observed that microparticle structures with a speed of 600 rpm requires about 55 μL/s speed to be pushed outside. The fluidic speed along the profile, obtained from COMSOL simulation, is depicted in Figure 5C. The magnetic microrobots are manipulated to the desired positions by altering the trapping centre. We utilized two types of microrobot structures (400 μm * 600 μm * 150 μm and 200 μm * 300 μm * 100 μm) to measure the flow profile. Figure 5D illustrates the flow profiles tested by the two types of magnetic microrobots. The magnetic microrobots are demonstrated with against-flow and localized flow sensing capabilities. The smaller microrobot exhibits higher resolution, resulting in
testing result more closely aligning with simulation outcomes. This flow-sensing method, based on dynamic magnetic trapping, holds promise for localized flow profile measurement with micro-scale resolution in complex and confined channels.

![Image](image_url)

**Figure. 5 Flow profile measurement with a microrobot in a curved flow channel.** (A) Curved capillaries. (B) Rolling microrobot in a curved flow channel. (C) COMSOL simulation of the fluidic speed in a curved channel. (D) Simulation and experiment of the fluidic speed along the profile as indicated in (B). Two types of microrobot structures were used: 400 μm * 600 μm * 150 μm and 200 μm * 300 μm * 150 μm.

**Conclusion**

We have demonstrated that dynamic magnetic tweezing enables the active trapping and retention of the magnetic microrobots in confined fluidic flows. We have uncovered unconventional motion modes exhibited by magnetic microrobots under the effect of dynamic magnetic tweezing fields within confined fluidic flows. The interplay between the rotating magnetic trap and the flow fluid results in the elastic displacement of the microrobot from the field centre, the distance of which can be modulated by the magnetic field frequency and flow speeds. Through the coupling of the magnetic field and fluidic field, multiple motion modes are realized, encompassing on-trap centre rolling, large-area revolution, off-trap centre rolling, and flown-off. Moreover, off-trap centre rolling facilitates local sensing of flow rate and flow direction around the magnetic microrobot. The manipulation scheme exhibits an intriguing flow field responsive characteristic, holding significant potential for localised sensing in micro-scale and confined spaces, as well as for in-vivo localized endovascular blood velocity measurement.

**References**

1 M. Yafia, O. Ymbern, A. O. Olanrewaju, A. Parandakh, A. Sohrabi Kashani, J. Renault, Z. Jin, G. Kim, A. Ng


Acknowledgements

Y.L. acknowledges financial support from the National Natural Science Foundation of China (52203152) and Shenzhen Outstanding Talents Training Fund (RCBS20221008093222008). G.L acknowledges financial support from Australian Research Council DECRA Fellowship (DE230100079).