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Magnetically driven microrobots moving in a flow: a review

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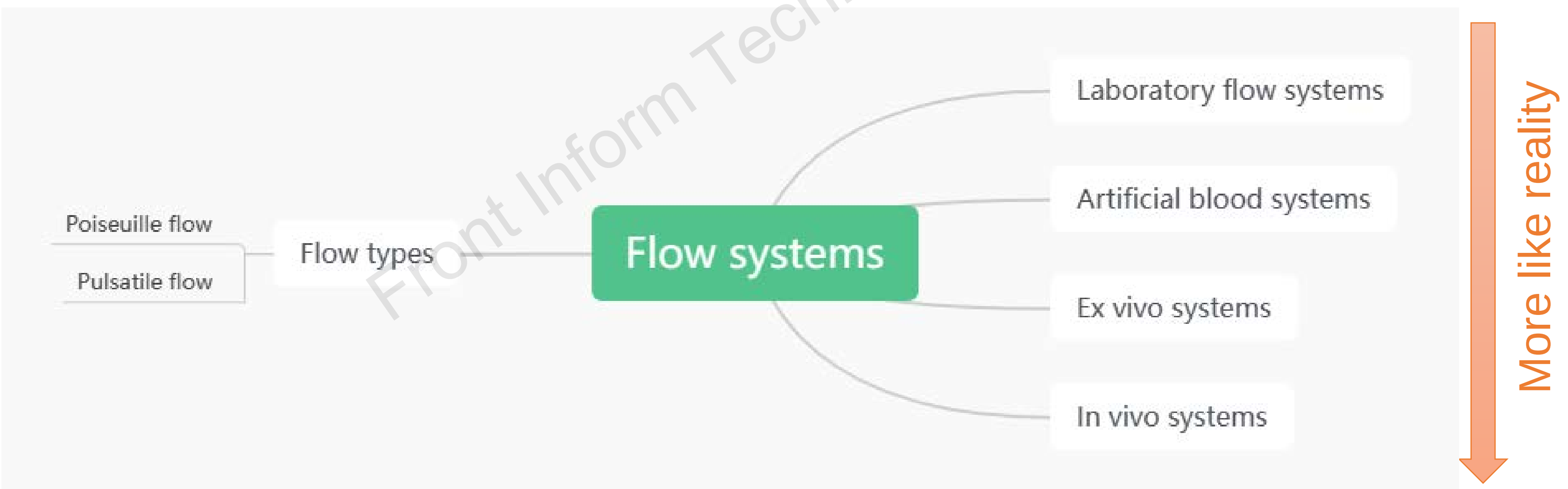
Motivation

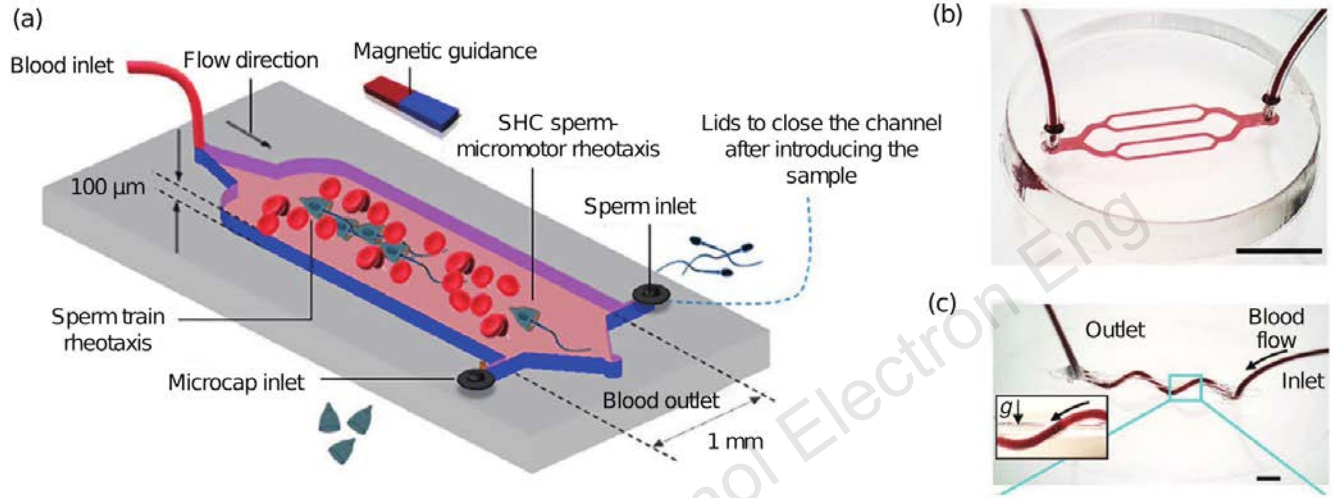
- What is our ultimate goal for a microrobot? Enable the microrobot to perform as a doctor, like in *Fantastic Voyage.* It is, however, too difficult to realize based on current resources.
- What is our contemporary goal then? Split the tasks into easier ones and solve them one by one. Thereinto, motion control in a flow is very important.
- How do scientists study and perform proper motion control? First, set up an appropriate experimental environment (whether mimicking human vessels or in real vessels); then study the mathematical model of the whole system (including the flow system and the microrobot); finally design a simple and effective control algorithm to perform the task.
- Our review is formulated based on the problem-solving path. We summarize the current applications, the three steps mentioned in the former paragraph with a review perspective, and the challenges that scientists are facing.

Flow systems: overview

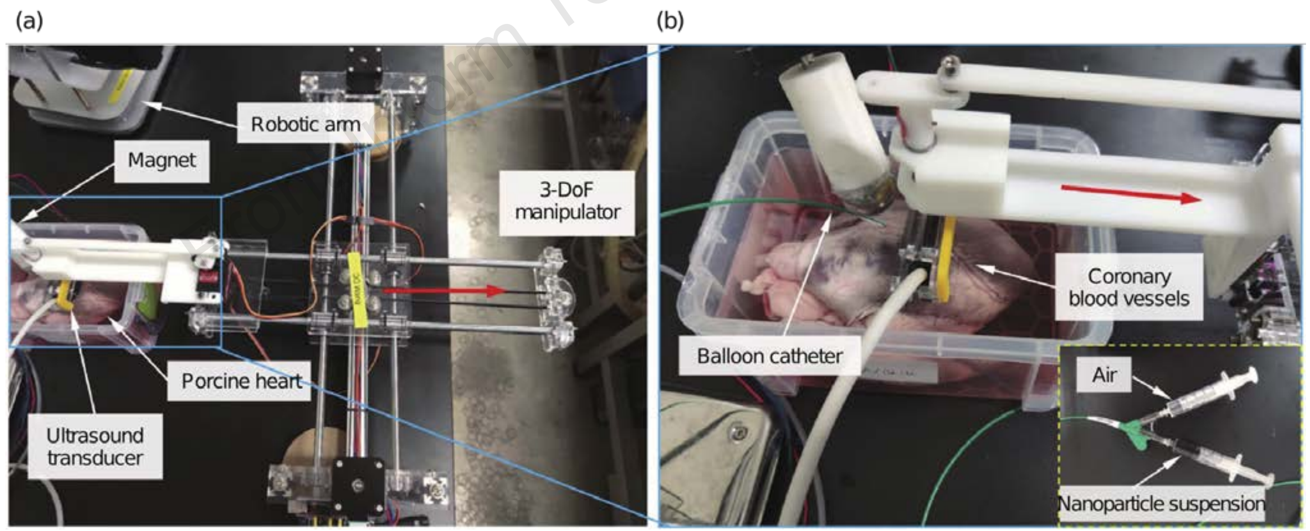
This part summarizes and exemplifies different flow systems, consisting of flow types (including Poiseuille flow and pulsatile flow) and different types of flow systems (based on their similarity to the real blood vessel system).



Flow system: examples



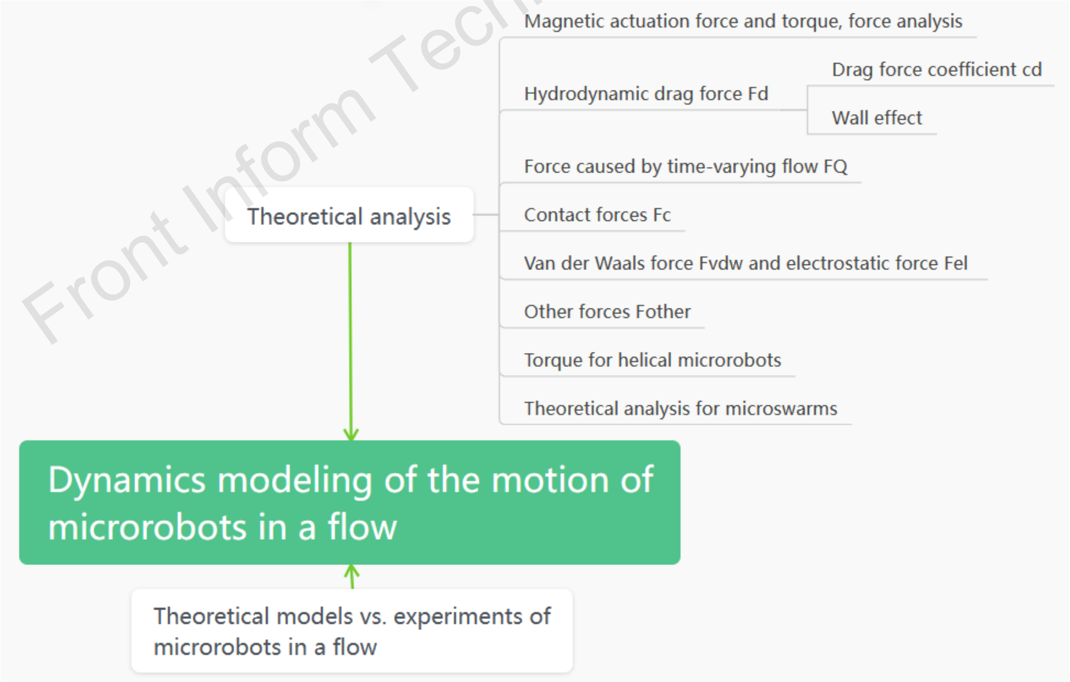
Examples of artificial blood systems: (a) from [1]; (b, c) from [2]



Examples of ex vivo flow systems: (a) and (b) both from [3]

Dynamics modeling of the motion of microrobots in a flow

Obtaining the model of the whole system is important for controlling the microrobot as planned. In this part, we give theoretical analysis (including magnetic actuation force, magnetic actuation torque, force analysis, six drag forces, and two complex examples) and discuss theoretical models vs. experiments.



Theoretical analysis

- We discuss force analysis and actuation, as well as torque actuation here. Factors that influence magnetic torques are summarized. Among them, drag force is concluded in detail, including drag force coefficient c_{d} and wall effect.
- As two special cases, helical microrobots and microswarms are discussed. Influencing factors on the motion of a helical microrobot (motion direction, channel size, magnetic field rotating frequency, and distance between the microrobot and the channel wall) and categories of microswarms in a flow (magnetic-interaction induced swarms, hydrodynamic-interaction-induced swarms, and weakly interacting swarms) are summarized.

Theoretical models vs. experiments of microrobots in a flow

Based on the theoretical analysis of forces, influencing factors, and the finite element method (FEM), tentative theoretical results of motion in a flow can be obtained. These results are compared to experimental results.

Comparison of microrobots' displacement based on analytical methods, FEM, and experimental methods [4].

Table 1 Displacement values under the analytical calculations from simulation results and experimental measurements, and error values in comparison with the experimental results at different flow rates from 1.0 to 4.5 mL/min

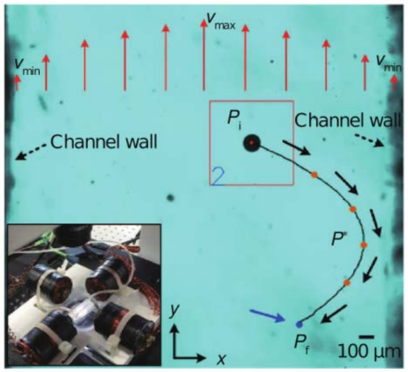
Parameter		1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
Displacement (μm)	Analytical	1119.7	2139.9	3365.3	4676.2	6243.3	9217.5	11 182.3	15 217.9
	FEM simulation	1113.8	2171.5	3297.7	4638.3	6389.8	8563.1	11 402.2	15 179.4
	Experimental	1196.6	2108.7	3462.0	4581.5	5972.8	9160.4	11 016.3	15 152.2
Error (%)	Analytical	6.43	1.48	2.79	2.07	4.53	0.62	1.51	0.43
	FEM simulation	6.92	2.98	4.75	1.24	6.98	6.52	3.50	0.18

Control strategies and methods

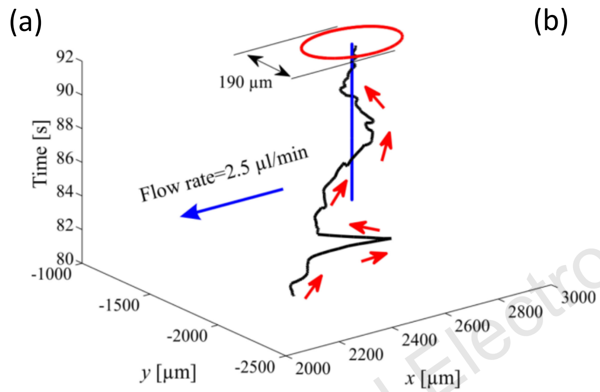
- The control outcomes, e.g., precision and response time, are closely related to the appropriate control methods chosen.

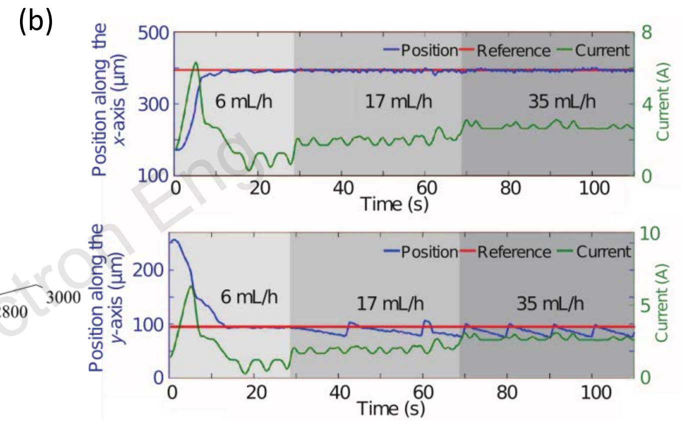
- Microrobot control methods are summarized:
  - ✓ Open-loop control
  - ✓ Proportional-integral-derivative (PID) control
  - ✓ Model predictive control (MPC)
  - ✓ Backstepping control
  - ✓ Extended state observer (ESO) based model-free control

Control examples

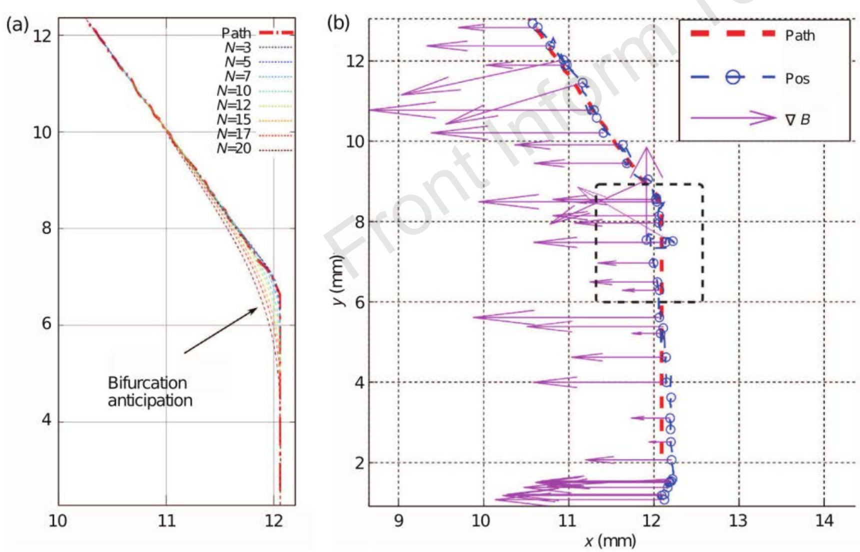


Example of open-loop control [5]

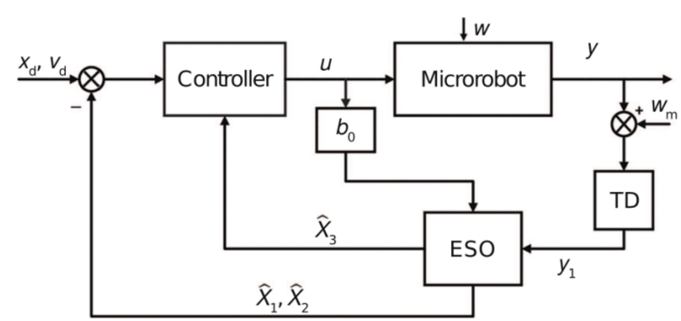




Examples of PID control: (a) from [6]; (b) from [7]



Example of MPC [8]



Example of model-free control [9]

Conclusions and outlook

- Magnetic microrobots have shown great potential in biomedical applications, such as embolization and drug delivery.
- Although many studies have been conducted, as summarized in this review, microrobot motion in a flow still has several challenges. The flow systems should be developed for more resemblance to the actual case. For complex systems, more accurate dynamics modeling is required. Image-based tracking and control of microrobots in vivo need further study. Moreover, the controller should be more robust to disturbances from the blood flow.

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