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Feedback Control of an Achiral Robotic Microswimmer

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Abstract

Magnetic microswimmers are useful for navigating and performing tasks at small scales. To demonstrate effective control over such microswimmers, we implemented feedback control of the three-bead achiral microswimmers in both simulation and experiment. The achiral microswimmers with the ability to swim in bulk fluid are controlled wirelessly using magnetic fields generated from electromagnetic coils. The achirality of the microswimmers introduces unknown handedness resulting in uncertainty in swimming direction. We use a combination of rotating and static magnetic fields generated from an approximate Helmholtz coil system to overcome such uncertainty. There are also movement uncertainties due to environmental factors such as unsteady flow conditions. A kinematic model based feedback controller was created based on data fitting of experimental data. However, the controller was unable to yield satisfactory performance due to uncertainties from environmental factors; i.e., the time to reach target pose under adverse flow condition is too long. Following the implementation of an integral controller to control the microswimmers' swimming velocity, the microswimmers were able to reach the target in roughly half the time. Through simulation and experiments, we show that the feedback control law can move an achiral microswimmer from any initial conditions to a target pose.

Keywords: microrobotics, magnetic control, low Reynold number, chirality, feedback control

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1 Introduction

The key to realizing the promise of using micro- and nanorobotics for diagnostics, minimally invasive surgery, drug delivery, and other potential medical applications is the control and manipulation of micro- or nanorobots in physiological environments. The concept of using micro- and nanorobotics to revolutionize biomedical applications is to operate on a patient with precision on the order of micro- or nanometer scale; in doing so, the treatment will be minimally invasive[1–14]. Nanomedicine, in particular, has shown great promise to improve mediated delivery to tumors[15,16]; however, the success of using nanoparticles for drug delivery depends on many uncontrollable environmental factors such as the circulation in the blood stream and diffusion inside tumor microenvironment[17]. The lack of a reliable and robust method to overcome environmental factors leads to poor drug accumulation on tumor cells[18]. This example illustrates the difficulty in using micro- and nano devices for biomedical applications due to strong influence from environmental factors. Indeed, previous studies have seen the increased influence from thermal diffusion as a swimmer change from microscale to nanoscale[19,20]. To overcome this limitation, recent researches have been done on applying external control modalities to manipulate micro- or nanoscale robots, swimmers, and particles[7,19–22]. Thus, there is a need to understand the kinematics of swimmers under low Reynolds number dynamics and to develop methods to control micro- and nanorobots.

At the microscale, swimmers are subject to the low Reynolds number condition, which means that swimmers in motion are not subject to inertial effects due to an extremely small inertial forces to viscous forces ratio[23]. The impact on the controllability of the microswimmers is that a swimmer can instantly move at the desired velocity and instantly stop. From the view-

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point of physics, most macroscale swimming methods do not work in microscale; as a consequence, microswimmers must use nonreciprocal motions for locomotion. Most previous examples utilized either chirality or flexibility to generate propulsion, as inspired by the scallop theorem[23]. The helical swimmers, analogous to the bacterial flagella, are the prime examples of chirality in microscale propulsion[24–30]. There are various incarnations of flexible swimmers, including the sperm-like swimmers with flexible DNA linkage[31] and the nanowire robots[32]; however, they are less common than their chiral counterparts due to the relatively high complexity to fabricate and control flexible materials for swimming. Other commonly known examples include the electrically- and optically-controlled bacterial microrobots[33], the magnetically steered swimming cells[34], optically-deformed 3-bead systems[35], the chemically-driven phoretic swimmers[36–38], and the biflagellate micro-objects[39].

Aside from dynamic constraints due to low Reynolds number, environmental factor is a prominent issue as we have mentioned. At the microscale, locomotive devices in fluid are subjected to strong diffusivity. This applies to both natural and artificial swimmers where their motion can be characterized as a combination of random fluctuation due to diffusion and active swimming due to propulsion[40]. Similarly, magnetic swimmers have shown the effects of Brownian motion on their trajectories at the micro- and nanoscale; evidently the smaller the swimmers, the higher the fluctuation in their trajectories[19,20]. In addition, small disturbances such as evaporation and vibrations that are imperceptible at macroscale will create unsteady and/or adverse flow conditions at microscale. Only a well-controlled laboratory setting can eliminate these environmental factors; therefore, it is important to consider such factors if microswimmers were to be applicable to real applications. Such factors are greatly enhanced as we move to smaller scale, such as the nanoscale.

In this work, we fabricate and magnetically control the achiral microswimmers. Upon actuation via a rotating magnetic field, the microswimmers convert rotation motion into translation motion. An achiral microswimmer consists of three magnetic beads that are firmly connected by chemical and magnetic forces. The three beads form an achiral structure with a length scale on the order of 10 μm. The achirality inherently leads to motion control uncertainties as a result of visually undetectable handedness[41]. It was shown previously that combining a fast rotating magnetic field, which actuates the microswimmers to swim, and a weak constant-intensity magnetic field is an effective countermeasure to eliminate such uncertainties[41]. The hydrodynamics and kinematics of the achiral microswimmer was thoroughly investigated in the previous work[42]. A qualitative kinematic model and a feedback control law were investigated in Ref. [41]. Furthermore, an integral (I) controller was implemented to compensate for uncertainties in the nonlinear relation between the frequency of the fast rotating magnetic field and the microswimmers velocity. While preliminary experiments were performed to validate the implementation of the controller[43], in this paper we present an in-depth systematic investigation of the feedback control of achiral microswimmers by testing the performance of the controller before and after the implementation of the I controller through experiments and simulations. This work improves significantly on the consistency of the results by using the same microswimmer for all experiments. The simulations presented here include Brownian disturbances and unstable flow in order to match real experimental conditions. To address the realistic environments in which the microswimmers operate, we also experimentally demonstrate the performance of the controllers under environment disturbances and unstable flow.

This paper presents results from experiments demonstrating the feedback control of the achiral microswimmers. The vision-based feedback control law is derived using our qualitative kinematic model and it can move an achiral microswimmer from any initial conditions towards a desired target position and orientation (i.e., target pose). The experimental data illustrate the feasibility of the feedback control and are an important step toward the precision motion control of microscale swimmers in bulk fluid.

The outline of the paper is given as follows. Section **2** describes the fabrication, geometrical properties of the achiral microswimmer, and the magnetic field control system. In section **3**, we introduce the models for the microswimmer's motion, the environmental disturbances, and the relationship between the swimming speed and rotation frequency. Finally, in section **4**, we introduce and implement a model-based feedback con-