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On-chip multimodal vortex trap micro-manipulator with multistage bi-helical micro-swimmer

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ABSTRACT

As recent developments in microrobotics open new fields of possibilities, micro robots are intended to be increasingly used in many fields. One of them is the possibility to work and study matter at microscopic scale without damaging their environment. This can be potentially useful in biological and medical field for precise non-intrusive work. Relying on last micro-robotic development and hydrodynamic manipulation and trapping we propose a multi-tasking bi-helical multistage micro-swimmer designed to generate local vortices for the manipulation and trapping of micro-particles in microfluidic working environment as a first step towards a new biocompatible non-contact micro-manipulator. With two motion modes and four manipulation modes, our design demonstrate his capacity to make long term transport and precise local manipulation and patterning of micro-particles of different sizes and matters.

1. Introduction

In many areas such as biology or chemistry, it is important to be able to precisely manipulate studied objects. Obviously, the size of biological objects can be really small and fragile like individual cells. However the manipulation and study of physical properties of such microscale objets is technically challenging. Most of the techniques developed in last decades for this purpose are based on electromagnetic effects. Optical tweezers [1–3], electrophoresis [4], dielectrophoresis [5] or magnetic tweezers [6] are the major ones, but all these methods have drawbacks for single cell manipulation. Optical tweezers need high power eletomagnetic waves, generating local warm up and degradation of materials [7]. Electrophoresis and dielectrophoresis are global effect make if difficult to handle single particles without special geometry of the workspace. And magnetic tweezers are unable to manipulate non-magnetic material and need the use of magnetic micro-particles as local point of attachment. Placed inside or outside of the biological material, theses micro-particle do not provide non-intrusive non-contact manipulation possibilities [8]. Recently, advances of micro-robotics technologies allow the opening of new handling methods for the microorganisms. Micro-manipulation with micro-swimmers [9,10] have been demonstrated but actually need a physical container for trapping particles and their mono-helical approach have stability and maniability drawback. Non-contact approach with hydrodynamic trapping has also been developed [11–15], but the technical approach remain basic with very simple geometric form only able to achieve one type of hydrodynamic trapping. To our knowledge, the only work of non-contact manipulation via hydrodynamic vortices generated by a helical micro-swimmer is the one from Peyer et al. in 2011 [16] and they are unable to trap particle, just moving them.

Our objective is to develop a new non-contact micro-manipulation tool towards applications in cells studies. It should allow precise manipulation and characterization of cells as much individual than at group, and the possibility to have automated functions. As first step we'll focus on "*in vitro*" tool, but we expect that *in vivo* will be possible in future. The objective of this paper is to propose a new design of semi-automated micro-robot allowing multi-tasking and better stability than previous work in the domain as demonstration of the possibility to have precise and robust non-contact manipulation of cell with micro-robot. For it we'll demonstrate *in vitro* manipulation of polystyrene micro-beads of dimension and density of same order of magnitude than cells and larger glass micro-beads. As proof of multimodal possibility of our design, theses manipulations have to be done by a single micro-swimmer.

Since the end of last millennium we know the high propulsion efficiency of bacteria flagella in low Reynolds number environment [17]. The helical geometry generate great propulsion power when spinning on his revolution axis. This effect inspired lot of recent works on microrobotic based on bio-inspired helical swim-

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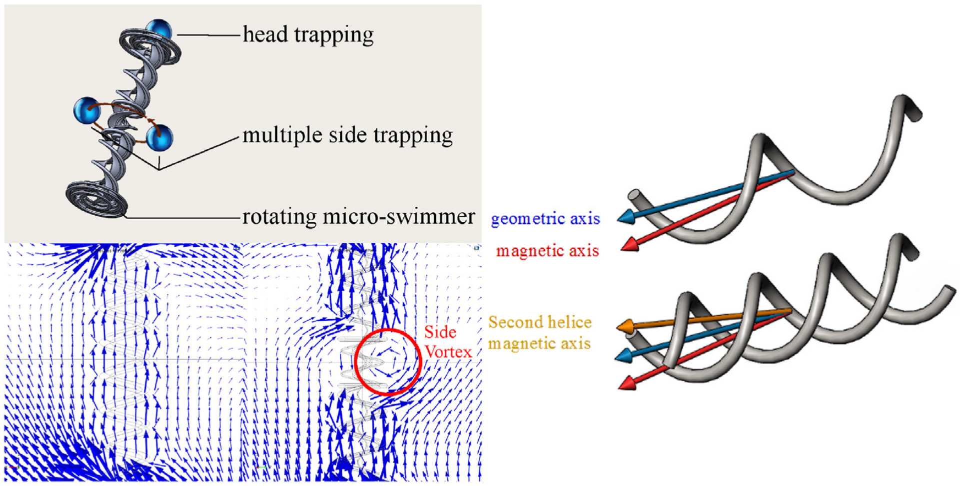

Fig. 1. Concept of trapped particle by vortex generated with helical micro-swimmer. top left: 3D concept of the final bi-helical design. bottom left: simulation of hydrodynamic flux generated by micro-swimmer rotating at 100 Hz. the left one is classical artificial flagella of 45,5 μm long and 8 μm diameter and the right on our mono-helical design (48 μm long and 8 μm diameter too with side vortex highlighted. The simulation was made at 100 Hz spinning frequency. The length of the arrows in the two simulations is not comparable because we have to apply a different multiplier to make them visible side by side. Right: Schematic of the bi-helical concept for compensation for inherent instability of magnetically actuated helical swimmer. The two magnetic axes will compensate for align global magnetic axis with geometrical axis of the swimmer.

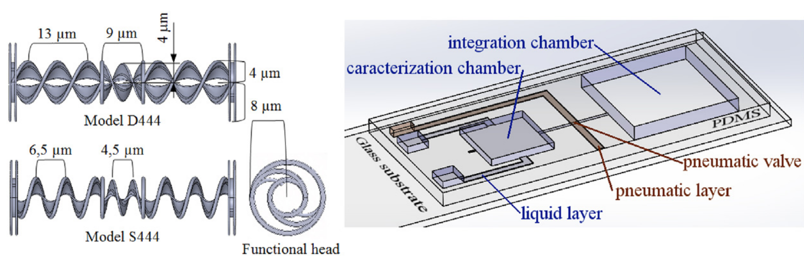

Fig. 2. Models Left: The two types of robot used. The S444 is a representative of classical mono-helical micro-swimmer and the D444 is the bi-helical model highlighted by this work. Right: 3D model of the microfluidic chip.

mer [10,18]. Based on this effect for propulsion, we propose to use specific design made of multiple stages of different helical geometries to generate local vortices around the robot. We've focus on two spots, one on the side on the swimmer with an inversed stage of the helix and the other at its ends with the addiction of functional head, as visible in top Fig. 1. The good 3D manœvrability and multiple mobility modes of microswimmers [18] makes these robot a dexterous tool. But the local flow around classical mono-staged helical swimmer don't allow trapping zone. We need to break the continuous flux, and the inversed part is done for it, as visible in middle Fig. 1, which, combined with the functional head, allows local trapping of particle with high stability. The head is based on recent hydrodynamics trapping works [11,14,10] at low Reynolds number and work in the same way. Moreover to reach our goal in terms of dexterous handling and automated control we need to deal with such inherent instability of magnetically actuated single helical swimmers [19,9] due to misalignment between geometric and magnetic axes of helical geometry. This results on a misalignment between geometric and rotational axes of the robot, schematized in bottom Fig. 1, and so perturbation of the maneuverability of the robot and on the hydrodynamic flux around it. As we need great stability of the response of the robot for allowing handling with automatic control we design new bi-helical swimmer composed of two coiled symmetric helix to align theses two axes. We use microfluidic chip as secured and stable workspace for micro-robot, ensuring identical experimental conditions. It will be our "*in vitro*" environment for the development of this new tool, and will be useful for future use with biological material.

In this paper we will explain first our theoretical and technical approaches, including fabrication process. Then we will develop the characterization test of two different models of robot we have conceptualized. And finally we will show the handling and manipulation possibilities obtained with this concept.

2. Systems and methods

2.1. Design and modeling

The major idea is to inverse the central part of the helical micro-swimmer, as visible on top Fig. 1. We expect that this inverted part made local counter-flux opposed to the global hydrodynamics around the robot. This generates local vortices near the robot which enable to trap particle. We have made simulation with a finite element model simulations software (Comsol) for pre-confirmation of this assessment. The results shown in bottom Fig. 1 reveal the presence of vortex sought. After few variation of length, diameter and number of pitch we selected for the experimental part two types of robots over the different possible designs. One mono-helical (type S444 presented in left Fig. 2) as a representative of classical helical micro-swimmers used in recent works but with central part inversed. And a bi-helical (type D444 presented in left Fig. 2) to prove the compensation of the natural instablity of the rotational axis of single helical robot [19]. The characteristics of theses helices are summarized in Table 1. They was chosen for having similar propulsion power between the two types by comparison of mean flux generated. However, the first tests show that the vortex effect