A contribution about ferrofluid based flow manipulation and locomotion systems

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Abstract. With the background of developing apedal bionic inspired locomotion systems for future application fields like autonomous (swarm) robots, medical engineering and inspection systems, this article presents a selection of locomotion systems with bifluidic flow control using ferrofluid. By controlling the change of shape, position and pressure of the ferrofluid in a secondary low viscous fluid by magnetic fields locomotion of objects or the ferrofluid itself can be realised. The locomotion of an object is caused in the first example by a ferrofluid generated flow of the secondary fluid and in the second and third case by the direct alteration of the ferrofluid position.

1. Introduction
With the background of developing apedal bionic inspired locomotion systems [1] for future application fields like autonomous (swarm) robots, medical engineering and inspection systems, this article presents a selection of locomotion systems with bifluidic flow control using ferrofluid. While [2] examines the topic theoretically, the present paper covers in the main applicational matters. Some aspects of the working principles underlying the systems will be discussed, for the aim is extracting the general out of the specific.

2. Classification
According to the definition [3] locomotion is no mere motion but the motion of the centre of mass and of the contact surface to the surrounding medium within a considered period. One has further to differ between passive and active locomotion systems. Whereas the ferrofluid volume in a passive locomotion system is locally fixed and affects the locomotion of a second object or fluid by local (mainly periodic) pressure and shape alteration, the ferrofluid portion of an active locomotion system is part of the locomotive structure and changes shape and position either by a local or global change of pressure. In the following one of the presented systems can be classified as a passive locomotion system. The other two fit in the group of active locomotion systems. All three apparatuses avoid the problem of enclosing the ferrofluid, a highly staining material, by using a secondary fluid as cover and support.

3. Passive locomotion system
The development of ferrofluid based bifluidic pump systems is an actual research field [4][5]. Known approaches provide a spatially changing electromagnetic field, e.g. generated by a
temporally shifted excitation of cascaded electromagnets, to cause time-dependent changes of pressure, shape and position of the ferrofluid. Hence, a travelling wave on the ferrofluid surface is generated so that a flow of the surrounding secondary fluid arises. These approaches have the disadvantage of great controlling effort and expenses. The presented system differs in its more simple construction, as the locomotion is generated by a periodically alternating magnetic field of a single electromagnet.

The device (Fig. 1) comprises either one or two separate ferrofluid portions, each locally fixed by a magnetic field of two opposite polarised permanent magnets below the vessel. The ferrofluid volume is set in a channel system filled with a second low viscous fluid.

**Figure 1.** Passive locomotion in the form of flow generation

top (left to right): Increasing global electromagnetic field (+EM+) enhances permanent magnetic (PM(+)) field and suppresses PM(-), ferrofluid shifts accordingly.

bottom: Field direction of (EM-) field changed polarisation, as (EM-) increases, PM(-) field is supported and PM(+) diminished, corresponding ferrofluid switches.

Process turns alternatingly. Ferrofluid movement and channel asymmetry induce channel flow of surrounding secondary fluid.

Once exposed to a global, homogeneous, alternating polarised electromagnetic field, the field of the opposite polarised permanent magnets is affected - subdued or supported, respectively - and accordingly the ferrofluid surface changes rocker-like altitude and pressure periodically. A directional channel flow of the secondary fluid is generated by this mechanism, which causes the locomotion of an object on the surface of the secondary fluid. By the use of a single ferrofluid portion a unidirectional flow, in case of two separate ferrofluid portions a bidirectional flow can be accomplished.

The system is experimentally analysed by two methods, particle image velocimetry and recordings by high speed camera.

Flow measurements with particle image velocimetry have been employed to analyse the flow generation and velocity within an excitation period of the electromagnetic field and the subsequent motion of the ferrofluid surface. The flow characteristics are manipulable by excitation frequency, magnetic field strength and the active time of each excitation polarisation within a period. The aim of the measurements is to gain knowledge of the functional parameters firstly for a maximum flow rate and secondly for uniform flow characteristics.

Figure 2 gives an exemplarily screen shot of a vector plot at a fixed time. One can see the secondary fluid flow along the central channel (Fig. 1) in a sideways perspective. Apart from the very left - the flow in direct vicinity of the ferrofluid actuator - a repeatedly arched mode with a globally directed flow can be recognised. In the top layers a middle velocity up to 10 mm/sec can be registered.

Theoretical considerations concerning the interaction between ferrofluid contour and the surrounding fluid dependent of the time within a excitation period will be verified experimentally by high speed recordings.
4. Manipulation system
Figure 3 indicates the general idea of swarm robotics. The behavior of fusing and splitting of ferrofluid portions as locomotive single unit or cluster is to be analysed using an localised, time-dependent electromagnetic excitation array while the ferrofluid portions are suspended in a secondary low viscous fluid. The flexible shape arrangement of the ferrofluid portions to an unit enables a form- and force-fit connection to one or more in the secondary fluid placed objects of complex contour. The following motion of the ferrofluid due to the change of the magnetic field provides controlled manipulation of the captured objects. The current settings allow to handle small objects up to 1 cm of size with available transporting forces of the range of approximately 0.1 N.

5. Active locomotion system
The last introduced example of a prototype (Fig. 4) refers mostly to bionic models. A single ferrofluid portion (in the range of 1.5 ml) moves uniaxial, bidirectional and actively in a low viscous carrier fluid. The locomotion is forced by a temporary, localised electromagnetic gradient field. A high velocity can be achieved, but in consideration of the controllability and the size of the vessel it should be limited to 10 to 15 millimeter per second.

6. Conclusion
In the article the aspect of ferrofluid based locomotion systems is given by the presentation of three bifluidic system for flow manipulation and locomotion of objects. While the description
comprises the parametric function and its realisation by constructions, which do not afford high expenses and control-effort, the prospect of further experimental or theoretical investigations, respectively, is given in future papers.

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References
[1] Zimmermann K, Naletova V A, Böhm V, et al. 2007 Verfahren und Vorrichtung zur Erzeugung einer apedalen translatorischen Bewegung (Deutsches Patent- & Markenamt) DE 10 2006 059 537 B3
[2] Zimmermann K, Naletova V A, Zeidis I, Turkov V A, Kolev E, Lukashevich M V and Stepanov G V 2007 A deformable magnetizable worm in a magnetic field - a prototype of a mobile crawling robot Journal of Magnetism and Magnetic Materials. 311 pp 450-53
[3] Forth E and Schewitzer E 1976 Meyers Taschenleizikon Bionik (VEB Bibliographisches Institut Leipzig) pp 229-30
[4] Park G S and Seo K 2004 New design of the magnetic fluid linear pump to reduce the discontinuities of the pumping forces IEEE Transactions on Magnetics 40 No.2 pp 916-19
[5] Ando B, Ascia A, Baglio S and Pitrone N 2006 Developement of Novel Ferrofluidic Pumps Proc. of the 28th IEEE EMBS Annual Int. Conf., New York pp 2828-31