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Development of Novel Ferrofluidic Pumps

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Abstract — **The development and realization of micropipettes and micropumps has captured the interest of people working in both biomedical and chemical areas for the capability of managing very low quantity of liquid (drug, biological liquid or expensive reagent) as well as everyone interested in controlling small flows for dedicated applications. In this paper a novel ferrofluidic pump adopting an electromagnetic actuation is proposed. The pump is realized by injecting three drops of ferrofluids into the pipe (two valves and a plunger are required) in the position where the pump must operate and by exploiting the forces produced onto each ferrofluid drop by some coils externally placed with respect to the pipe. The absence of any mechanical moving parts, the possibility to realize a volumetric pump in a section of an existing pipe without interruptions and deformation are the main advantages of the architecture proposed as compared to existing prototypes. A detailed description of the strategy proposed is presented along with a preliminary characterization of the prototype developed.**

I. INTRODUCTION

Microfluidic devices have the major application in bio medical field (diagnostic, drug delivery, genetic sequencing) and chemical field (chemical analysis and syntesys). To this aim, low cost and disposable device are valuable.

The possibility to manage very low liquid volume with a high accuracy is the main advantages of these innovative solution as respect to conventional pipette. The ability to handle small volumes of fluids is important to decrease the consumption of expensive reagents, moreover efficient drug delivery systems can be considered if suitable pumps would be available. This is problematic because a high precision is requested and the conventional pipettes can sample an aliquot of liquid as small as 0.2 to 0.5 microliters with a precision ranging in 3-5% [1]. New technological demands in biochemical laboratories have motivated the search for methods of handling volumes of liquid smaller than 0.2 microliters.

Actually micropipettes [1], alternative micropumps and valves [3], [5], rotative micropumps [4] and electromagnetic micropumps [6] are available which use non conventional materials to implement the pumping operation.

In particular, ferrofluids are considered one of the most suitable material for the implementation of microfluidic actuators due to their intrinsic mechanical and magnetic properties [2]. Moreover, the availability of biocompatible ferrofluids encourages the use of such solutions for bio-medical application.

Ferrofluids are synthetic liquid constituted by colloidal suspensions of ultra-fine (5-10 nm), single domain magnetic particles in either aqueous or non-aqueous solution [2]. If a magnetic field is applied, the fluidic state is maintained but particles align in the direction of the field and move in a more compliant position, thus causing viscosity and therefore density variations that are proportional to the intensity of the field applied. Exploiting these properties, a pipe, containing a ferrofluidic volume, can be capped by a strong magnetic field, as well as a suitable plungers can be implemented.

In this work a novel architecture implementing a ferrofluidic pump with electro-magnetic actuation is proposed.

The pumping strategy implemented is free of mechanical moving parts, thus avoiding stress and increasing the life time of the device. Moreover, due to the actuating strategy the pump can be realized by exploiting a section of an exiting pipe without damaging or modifying the existing structure, thus increasing the flexibility of the methodology proposed. The latter is valuable for applications where the pump must be installed in a specific location (e.g. vascular surgery application). Moreover, a continuous pumping operation can be guaranteed.

In the following sections, a detailed description of the pump working principle and the actuation strategy are given along with preliminary results of the prototype characterization. Actually, standard performance indexes are used to investigate the efficiency of single parts (valves and plungers) as well as to estimate the overall behaviour of the ferrofluidic pump prototype developed.

II. AN OVERVIEW OF THE FERROFLUIDIC PUMP

In this section the architecture of the pump is highlighted and the working principle behind the novel pumping strategy implemented is introduced. The main idea is to move a small amount of liquid in a glass channel by exploiting an electromagnetic actuation system distributed along the pipette. The working material adopted to actuate the pumping mechanism is a colloidal suspension of magnetic particles known as Ferrofluid [1].

A. *The prototype implementation*

In order to implement the pumping mechanism two ferrofluidic valves and a plunger are realized along a glass channel with an inner diameter D_c=4.4 mm. To implement the valve/plunger a drop of ferrofluid is injected into the corresponding section of the pipette (three drops for the case considered adopting two valves and one plunger). These ferrofluidic volumes are electromagnetically actuated by external coils as shown in Figure 1. In the figure some other geometrical quantities are reported.

For the valve implementation, a 0.05 ml volume of ferrofluid is injected into the dedicated section, while two electromagnets with the symmetry axis perpendicular at the fluid flow are used to control the ferrofluid shape. Figure 2a shows the strategy adopted to operate the valve. In order to implement the OPEN/CLOSE states a suitable driving of the external coils is required. Actually, the OPEN state is obtained when the magnetic field imposed by the bottom coil is High and the magnetic field of the top coil is Low, thus flattening the ferrofluidic volume and allowing fluid flow through the channel. The CLOSE state is obtained when a high field is produced by both the top and bottom coils; in this case the ferrofluid volume creates a cap in the channel which blocks the fluid flow.

The plunger mode requires the use of three electromagnets with the symmetry axis perpendicular at the fluid flow are used. In this case 0.1 ml of ferrofluid is injected into the plunger section. A scheme of the plunger operation is drawn in Figure 3a. To indicate the field intensity applied by any coil a grey scale code is used. The states allowed for the plunger are LEFT, RIGHT and OPEN, which can be obtained by the following coils control protocol:

- LEFT: coils BP1 and BP3 ON and coil BP2 OFF, so the ferrofluid create a cap in the cannel arranged between BP1 and BP3 coil;
- RIGHT: coils BP2 and BP3 ON and coil BP1 OFF, so the ferrofluid is arranged between BP2 and BP3 coils;
- OPEN: coil BP3 ON and coils BP1 and BP2 OFF, so that BP1 flattens the ferrofluid in the channel.

The fluid pumping is established by the variation from LEFT to RIGHT or from RIGHT to LEFT, so the cap of ferrofluid pushes the liquid in the channel. The OPEN state is used to put the plunger in the opposite state (LEFT or RIGHT) without a considerable action on the fluid.

Figures 2b and 3b are real views of the valve and plunger prototype, respectively. Figure 4 is a real view of the whole pumping system.

The next section describes the actuation sequence of the valves/plunger implemented to produce a liquid flow inside the pipette.

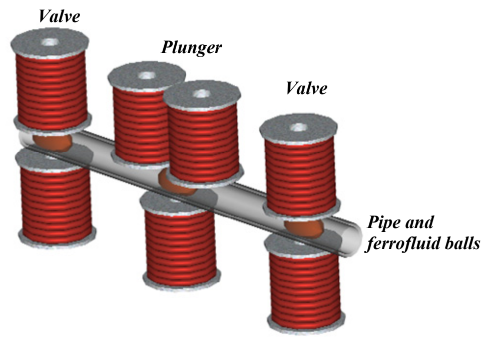

Figure 1. The ferrofluidic pump design model

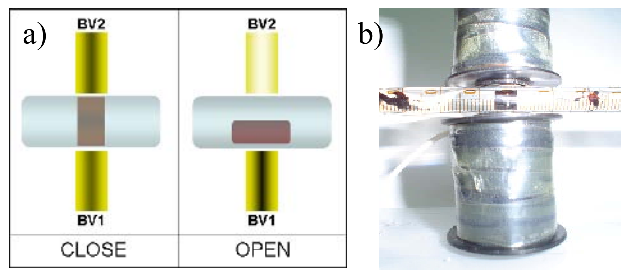

Figure 2. schematic of the operative principle of the valve (a) and a photo of the valve prototype realized (b) to indicate the magnetic field intensity in the coil the grey scale is used.

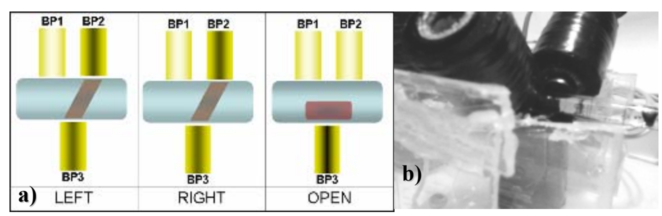

Figure 3. The schematic of the operative principle of the plunger (a) and a photo of the plunger prototype realized (b). To indicate the magnetic field intensity the grey scale is used.

B. *The driving strategy*

The pumping protocol, schematically drawn in Figure 5, can be summarized in the following steps:

a) The valves are open and the plunger is in the left position, ready to suck up and push the liquid (Figure 4.a);

b) The valves are still open and the plunger state change from left to right position so to suck the liquid (Figure 4.b);

c) The valves are closed so to obstruct the channel and the plunger remain in right position (Figure 4.c);

d) The valves are still close and the plunger goes to open position to allow the liquid distribution in the channel (Figure 4.d);

e) The valves are still close and the plunger go to left position ready to restart the sequence (Figure 4.e).

The pumping sequence is summarized in Table 1.

Figure 4. The experimental prototype used in this work. The valve two coil in the left realize the valve while the three coil in the right relize the plunger.

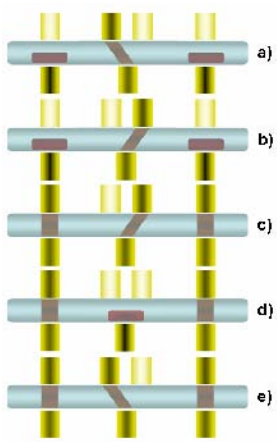

Figure 5. schematic of the fluid pumping sequence.

TABLE I. FLUID PUMPING SEQUENCE

Fluid Pumping Sequence			
Step	***Valve_in state***	***Plunger State***	***Valve_out state***
a)	OPEN	LEFT	OPEN
b)	OPEN	RIGHT	OPEN
c)	CLOSE	RIGHT	CLOSE
d)	CLOSE	OPEN	CLOSE
e)	CLOSE	LEFT	CLOSE

To manage the pumping sequence a Bit string is used. The Bit string consists of three bits [bp2 bp1 bv2] (this notation has been chosen for coherence with the actuators notation): the Least Significant Bit controls the valves state through the top driving coils, while other two bits, bp1 and bp2, are dedicated to the top coils, right and left respectively, of the plunger system. Concerning the valve actuation, a bit 0 indicates the OPEN state while a bit 1 is used for the CLOSE state. The Bit string sequence implementing the whole pumping protocol represented in Figure 5 is summarized in

TABLE II. BIT STRING IMPLEMENTING THE PUMPING PROTOCOL

Step	**Plunger state**	**bp2**	**bp1**	**Valve state**	**bv2**
a)	LEFT	0	1	OPEN	0
b)	RIGHT	1	0	OPEN	0
c)	RIGHT	1	0	CLOSE	1
d)	OPEN	1	1	CLOSE	1
e)	LEFT	0	1	CLOSE	1

C. Notes on the hardware implementation

Figure 6 shows the conditioning electronics adopted to drive the valve coils. It consists of a buffer section followed by a Voltage to Current converter to drive the actuating coils. Each coil is independently controlled through a digital signal provided to the buffer state.

Electronic for driving the plunger coils is drawn in Figure 7. The signal conditioning scheme is the same adopted for the valve actuation while in this case two coils have to be controlled. Also in this case two digital signals are used to control the status of each coil.

The generation of the digital string is relied on a Data Acquisition Board connected to a Personal Computer. A dedicated user interface, developed in the LabVIEW environment, is used to generate the sequence of digital string implementing the pumping protocol. This solution has been adopted for the sake of convenience due to the flexibility required during the development phase. Actually, the same digital actuation sequence could be generated through a microcontroller based architecture, thus reducing costs and improving the manageability of the whole system.

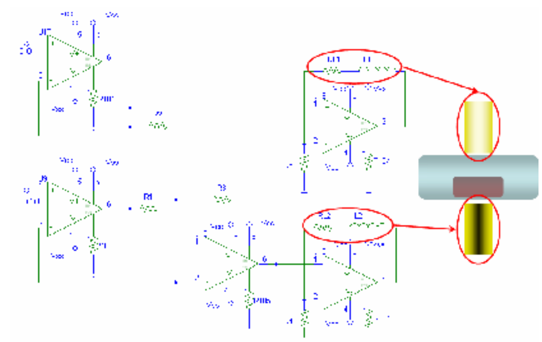

Figure 6. Schematic of the driving electronics for the valve coils

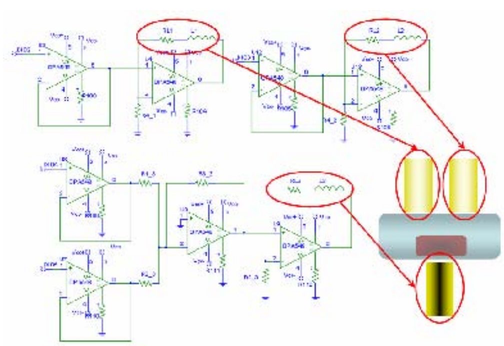

Figure 7. Schematic of the driving electronics for the plunger coils

III. A PRELIMINARY CHARACTERIZATION OF THE DEVICE

The fluid sampled by ferrofluidic plunger in each pumping cycle can be estimated through the following expression:

$$V_f = d_m \cdot A \quad (1)$$

where d_m is the medium way of the centre of the ferrofluid volume (implementing the plunger) in the passage from one state to another state, and A is the section of the channel.

In the case of a circular section channel, as the one adopted for the prototype described in this paper, with diameter D_c, equation (1) becomes:

$$V_f = d_m \cdot \pi \cdot \frac{D_c^2}{4} \quad (2)$$

For the prototype developed an estimated value of 0.7 mm has been experimentally obtained for the parameter d_m, thus producing the following estimation of the volume handled at each cycle: V_f= 0.1 ml.

It must be observed that this feature can be easily modified by modulating the distance between the top driving coils of the plunger system or modifying the volume of the ferrofluid mass.

Considering that the fastest actuation cycle assuring a reliability of the pumping operation has been experimentally estimated as lasting as 5 s, it can be affirmed that the pump prototype developed can assure a flow rate of 1.2 ml/min.

This estimation has been confirmed by experiments dedicated to monitor the average amount of pumped liquid over a surveys of several pumping cycles. To implement this experimental set-up the pump prototype has been plugged into graded source tank and a destination tank. After performing several pumping cycles an estimation of the actual flow rate has been accomplished through the measurement of the residual volume in the source tank. Results of this experimental survey confirmed the previously estimated flow rate.

Another interesting result is given in Figure 8 where the drop pressure of a valve as a function of the driving current of the actuating coil is reported. This result was obtained through arranging a pressure reference system connected to the glass pipe housing the valve device. For each driving current, the valve (set to the CLOSE state) was forced with increasing pressure until the cap breaks. This limit regime was assumed as a measure of the drop pressure.

IV. CONCLUSIONS

In this work a novel ferrofluidic pump is presented. The pump allows for continuous fluid pumping with a limited number of components. The pump architecture presented can be considered a preliminary step toward the realization of micro-pump implementing the same principle of actuation.

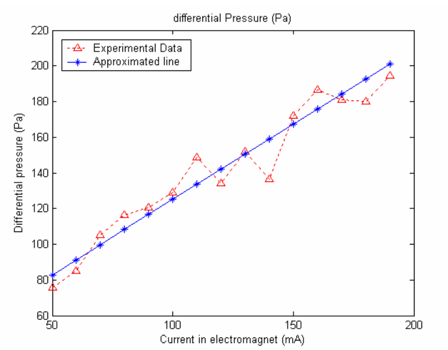

Figure 8. Drop pressure of valve system as a function of the coil s driving current

Actually, the prototype presented through this paper aims to demonstrate the working principle of the developed strategy. Although the measured performances are far from the currently available solutions due to the preliminary prototype implementation (electromagnets size, pipe dimensions, conditioning electronic) above mentioned advantages of the proposed methodology encourage the development of new prototypes exploiting the working principle declared. In particular, efforts will be dedicated to optimise the pump design, to reduce both the minimum amount of ferrofluidic liquid required to implement the pumping mechanism as well as the minimum volume handled by the pump.

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