Abstract— Flagellar swimming is one of the swimming methods used by micro-organisms to advance in aquatic environment. The undulating motion of the flagella was successfully imitated to create propulsion for a medical swimming micro robot. The influence of a head section on the performance of such a robot is shown analytically. Swimming experiments demonstrate forward and backward swimming of a novel magnetically driven swimming tail. We intend to use the flagellar swimming tail in a three tail configuration for neurosurgical intervention in the ventricular system.

I. INTRODUCTION

The late advances in smart pills [1] shows the advantage of an untethered device to reach previously inaccessible parts of the human body. Such a device can be a powerful diagnostic tool but it fully depends on the intestines peristaltic motion. In order to be able to do intervention or reach places where there is no natural driving force, one has to add self-propelling ability to the smart pill [2]. For example in the brain's ventricular system there are flows in the order of 1 [mm/s] (see [3]), but in contrary to the small intestines it will not insure that the smart pill will reach its target, thus positioning actuators are essential for the system.


Micro robots swim in low Reynolds number fluidic regime, for example a typical 0.1 mm micro robot that swims in water with a velocity of 1 mm/sec has a Reynolds number of 0.1. Due the reversibility in low Reynolds number flow (e.g. Stokes flow) the action of swimming micro organisms in nature are different from regular size swimmers such as fish [9]. All the micro swimming mechanisms such as spermatozoa [10], cilia [11] and amoeba [12] create in one way or another a traveling wave, advancing in the opposite direction of the micro organism's locomotion. The simplest swimming method for a micro system is flagellar swimming by creating a planar or helical [13] traveling wave in an elastic tail. Fig. 1 compares between swimming of the spermatozoa of the lugworm Arenicola marina and the planar traveling wave created by a piezoelectric swimming tail [14].

One can observe the similarity of the bending traveling wave to the spermatozoa's locomotion.

This paper presents in section II a theoretical model that calculates the influence of a head section on swimming, reports in section III on experimental results of swimming with a magnetic tail and introduces in section IV a robot design for a neurosurgical medical application.
II. THEORETICAL RESULTS

The swimming theory we developed was published in detail in previous publications. In this paper we present the influence of a head section on the swimming of a micro robot. For further details on swimming by creating a traveling wave in an elastic beam in viscous fluid see [4].

A. Swimming tails

We are using two methods to create the propulsive force in the elastic beam:

1) Piezoelectric bimorph bender – This actuator uses a piezoelectric bimorph to create the traveling wave (see Fig. 2). The outer electrodes of the bimorph are divided into three sections \{V_1;V_2;V_3\} with the same frequency \(\Omega\) and different amplitudes \(\{G_1,G_2,G_3\}\) and phases \(\{\Phi_1,\Phi_2,\Phi_3\}\).

2) Magnetic coils – a set of three coils are glued in series on a flexible printed board. Similarly to the previous method the coils are driven by three signals. In the presence of a static magnetic field, \(B_o\), the Lorenz force:

\[ F_L(t) = N_i b_i I_i(t) B_{lb} \]  

where \(N_i\) is the number of turns in the i-th coil, \(b_i\) is the width of the coil and \(I_i(t)\) is the current in the coil, creates a moment in each coil (see Fig. 3):

\[ M_i(t) = I_i F_L(t) \]  

The combination of the three moments creates a traveling wave along the tail.

B. The Heads Influence on Swimming

In a self propelled swimming body moving with constant velocity, the propulsive force is equal to the drag force of the body. The propulsive force of the swimming tail can be calculated from the drag force of a cylindrical rod. The explicit form of this force is [15]

\[ F_p = \frac{2\pi \mu U}{\ln(L/2c_0) + 0.19315} \]

where \(\mu\) is the viscosity of the surrounding fluid, \(L\) is the length of the swimming tail, \(U\) is the velocity of the swimming tail and \(c_0\) is the first coefficient of the cross section shape function’s Fourier decomposition.

Assuming that the influence of the head on the flow around the swimming tail can be neglected, the reduction in the propulsive velocity of the micro robot due the addition of a head section can be calculated from the following equation:

\[ F_{p+}(U_{+}) = \frac{2\pi \mu U_{+} \ln(L/2c_0) + 0.19315}{\ln(L/2c_0) + 0.19315} \]

Where: \(U_{+}\) is the reduced propulsive velocity and \(F_{p+}(U_{+})\) is the drag of head of the micro robot. The drag force of the different head shapes is [17]:

\[ F_{p+}^{(h)}(U_{+}) = 6\pi \mu R U_{+}^{(h)} \]

\[ F_{p+}^{(d)}(U_{+}) = \frac{32}{3} \mu R U_{+}^{(d)} \]

\[ F_{p+}^{(r)}(U_{+}) = \frac{2\pi \mu L}{\ln(L/2R_0) + 0.19315} U_{+}^{(r)} \]

Where: \(F_{p+}^{(h)}(U_{+})\) is the drag force of a sphere with radius \(R\), \(F_{p+}^{(d)}(U_{+})\) is the drag force of thin disc with radius \(R_d\) and \(F_{p+}^{(r)}(U_{+})\) is the drag force of a rod with length \(L\) and radius \(R_r\).

The velocity reduction ratio between of the different head shapes is:

\[ \frac{U_{+}\eta}{U} = \frac{U_{+}\eta}{3R_0 + \eta}; \frac{U_{+}\eta}{U} = \frac{U_{+}\eta}{1.6976R_0 + \eta}; \frac{U_{+}\eta}{U} = \frac{\eta}{\eta + \eta} \]

Where:

\[ \eta = \frac{L}{\ln(L/2A) + 0.19315}; \frac{L}{\ln(L/2R_0) + 0.19315} \]
Fig. 4 presents the reduction of the velocity for different volume ratios. The volume number is defined as ratio between the volume of the head and the volume of the swimming tail, \(\frac{Vol}{LBT}\). In order to estimate the volume of disc we assumed that the disc thickness is fifth of its diameter, i.e. \(t_d = 2R_d / 5\). The same ratio was also assumed between the cylinders length and diameter, i.e. \(L_c / 2R_c = 5\).

Fig. 4 shows that the most efficient form is the flat disc
\[ I_1 = i_0 \sin 2\pi\Omega t \]
\[ I_2 = 2i_0 \cos 2\pi\Omega t \]
\[ I_3 = -i_0 \sin 2\pi\Omega t \]  \hspace{1cm} (8)

where \( i_0 = 1.12 \text{[mA]} \) designates is the signal amplitude and \( \Omega \) is the frequency of the signals which has been varied between 10 and 125 [Hz] In order to achieve swimming backward we reversed the phases of the signals in (8).

Fig. 6 shows the scheme of the experimental setup. The weight of the tail was \( m_2 = 0.073 \text{[g]} \) and the total weight of the wire was \( m_1 = 0.29 \text{[g]} \).

From the deflection of the tail from its equilibrium point we can calculate the propulsive force:

\[ F_p = \left( m_2 - \rho \Delta \frac{L B T}{T} + \frac{m_1}{2} \right) g \frac{\Delta}{T} , \]  \hspace{1cm} (9)

where \( \rho = 997 \text{[kg/m}^3\text{]} \) is the density of the fluid (water), \( g = 9.81 \text{[m/s}^2\text{]} \) is gravity and \( \Delta \) is the maximal distance the tail achieved.

Fig. 7 illustrates the swimming of the magnetic tail. The tail is driven with a frequency of \( \Omega = 25 \text{ [Hz]} \) and amplitude of \( i_0 = 1.15 \text{ [mA]} \). The image shows motion of the tail forward and backward.

In this experiment the swimming tail moved 9 [mm] forward and 5 [mm] back which are equivalent to a propulsive force of 10.3 [\mu N] and 5.7 [\mu N] accordingly.

Fig. 7. Swimming of the magnetic tail forward (the upper 7 images) and backward (the lower 5 images). The vertical white line denotes the initial location of the tail.

![Graph showing propulsive force versus frequency in forward (blue line with plus markers) and backward (red line with x markers) swimming of the magnetic swimming tail.](image)

The magnetic swimming tail was tested in several frequencies from 1 to 150 [Hz], Fig. 8 summarizes the results of those experiments. The lower the frequency the larger the propulsive force. The first natural frequency of the tail was found at \( \omega_0 = 110 \text{ [Hz]} \), we did not find any change in the decay of the swimming velocity at this frequency. When the phase difference between the coils is zeroed there is no propulsion. This result emphasizes the importance of undulating motion in small dimensions.

The Re number for the experiments is about 300 which is clearly a laminar flow, thus we will present in the future a proper swimming model based on earlier works on swimming of small fishes.

IV. MEDICAL APPLICATION

A flagellar swimming tail can be utilized for a large variety of bio-medical tasks. These medical applications include:

1) Examination of the gastrointestinal tract, including inspection of and intervention in the: esophagus, stomach, small intestine, colon and rectum [1].

2) Brain or spine inspection or surgery through the cerebrospinal fluid [4].

3) Thoracoscopy using a fluid to fill the chest cavity.

4) Kidney stone destruction [17].

5) Eye surgery [7].

6) Fetal surgery [18].

In general, flagellar swimming may fit any bio-medical application in which a robot advances in fluidic media. It can be proven that reducing the space in which micro-robot advances increases the efficiency of its swimming.

It has to be noted that flagellar swimming can hardly be useful for cardiovascular applications because of the fast velocities of the blood stream.
A. Swimming micro robot for brain surgery

One of the applications of a flagellar swimmer is interventions in the ventricular system in the brain.

Anatomically both the brain and the spinal cord (CNS, Central Nervous System) are immersed in transparent fluid similar to water, known as the CSF (Cerebrospinal fluid). The CSF is produced in the ventricles of the brain and flows out of the ventricular system to the subarachnoid space (SAS). This space covers both the brain and the spinal cord and connecting the internal cavities of the brain with the outer surface of the CNS. Theoretically, this space can be a conduit for introducing imaging and interventional devices that can reach pathologies without the need for conventional operative methods.

There is a genuine need to explore these pathologies by minimally invasive methods for diagnosis, biopsies and ultimately for surgery. Ventriculoscopy is well established for treating lateral and third ventricle pathologies using mostly a rigid endoscope. Such a device has many limitations in the soft environment of the CNS. Currently, endoscopes are introduced through a cannula into the lateral ventricles. When using rigid endoscopes, an opening of a diameter of Ø10 [mm] in the brain is necessary in order to reach the target area. Since the surgeon wants to minimize damage to the brain, he needs to insert the endoscope as close as possible to the surgical target. Such a minimal distance approach, however, can endanger other parts in the brain and may damage them.

Flexible endoscopes are partially solving the problem but they still offer only limited access due to external tethering. We propose to use a swimming micro robot (although the robot itself will be about 1-2 [cm³] in size, its components will have to be produced by micro technologies) to perform the intervention. The device can be inserted through a cannula crossing a (potentially remote) functionally blank brain area but still could reach its target area without any strong spatial constraints.

We suggest the following interventional protocol for the robot:

1) Inserting a 6.6mm diameter cannula into the lateral ventricle through the right-frontal or right-parieto-occipital bone without jeopardizing functionally vital areas (standard procedure for ventriculostomy);
2) Introducing the robot through the cannula into the lateral ventricle;
3) Navigation in the ventricle to reach the target area;
4) Inspection of the target area by high resolution imaging and local investigation of the electrical neuronal activity by the robot’s built-in electrodes.
5) Targeted intervention: force guided biopsy, local chemotherapy or placement of radioactive agents for brachytherapy. If sufficient power is available, ablation or cauterization can also be carried out.
6) Returning of the robot to the insertion point, and docking to the cannula.
7) Retrieving the robot and the cannula.

Fig. 9 illustrates the introduction of the swimming robot into the ventricular space.

The critical components in the robot are the following (See fig. 10):

1) Three flagellar swimming tails that pop out of the robot's body after introduction into the ventricle. The propulsion enables swimming in 5 degrees of freedom.
2) Power source made of batteries or magnetic coils for RF induction.
3) Custom designed IC for command, control and communication.

The payload for the robot will include:

1) Endoscopic camera [19] and LEDs.
2) Force sensor array to transmit tactile information and to increase the safety (warning of collision with the ventricle walls).
3) A magnetic tracking sensor for localization [20].
4) Micro tools for biopsy, and holding and deploying radioactive agents for brachytherapy.

Fig. 10. Conceptual assembly of a swimming micro robot for neurosurgery. The components of the robot are: 1) Three swimming tails, 2) Power source (here 5 Renata ZA10 batteries in series), 3) Packaged IC for command control and communication, 4) Antenna, 5) Endoscopic Camera, 6) LEDs, 7) Force sensors, 8) Tool for intervention, 9) Localization sensor (here an Aurora magnetic tracker receiving coil).
This swimming robot has a diameter of Ø6.6 [mm] (determined mostly by the diameter of the batteries) and a length of 31 [mm] which results in a net volume of 1.1 [cm³]. The propulsive units’ angle with the axis of the body is 30° and the outer diameter of the robot with open swimming tails is Ø26 [mm].

Such a robot will be able to swim with a velocity of about 1 [mm/s] in its axial direction. As it was shown earlier, for an operating period of 1 [hr], one hearing aid battery is necessary. The remaining batteries will be used mainly for powering the LEDs and the camera which are the main power consumers (the power consumption of the rest of the components can be neglected). The communication will be able to transmit to a distance of about 0.5 [m] and will operate bidirectionally.

V. CONCLUSION

In this paper we present new theoretical and experimental results towards utilizing flagellar swimming for medical application. To the best of our knowledge this is the first time demonstrating bi-directional swimming experimentally for planar wave propulsion. The theoretical results enable calculating the swimming properties of a combination of swimming tails and a head section. In addition, we propose a clinical procedure which can use flagellar swimming for propulsion and steering.

In the future we intend to realize the swimming robot described in section III for ventriculostomy and present a model that explains the experimental results presented in this work.

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