Miniature Ferromagnetic Robot Fish Actuated by a Clinical Magnetic Resonance Scanner

Frédéric P. Gosselin, David Zhou, Viviane Lalande Student Member IEEE,
Manuel Vonthron Student Member IEEE and Sylvain Martel Senior Member IEEE

Abstract—A new actuation principle which permits omnidirectional steering for a swimming robot using a magnetic resonance imaging scanner is presented. The robot fish is made of a ferromagnetic head and a flexible tail. It is actuated by transverse oscillating magnetic gradients. The swimming performances of the robot fish are studied for varying tail length as well as varying actuation frequency and amplitude. Through a dimensional analysis, the important parameters influencing the swimming gait are identified and the mechanism of actuation is better understood. Considering the scaling of forces, this dimensional analysis leads us to believe that in the future the height and width of the fish robot could be miniaturised to sub-millimetre scale.

I. INTRODUCTION

Wireless microrobots offer great promises in the development of new minimally invasive procedures [1]. We envision microrobots small enough to be swallowed or injected in the arterial system to navigate the natural pathways of the human body and perform missions of drug delivery, endoscopy or microsurgery. The benefits in terms of better performance of treatment and diagnostic as well as reduction of side effects are exemplified by the success of gastrointestinal-track capsule endoscopy [2] now in use for diagnosis.

The gastrointestinal-track capsule endoscope is swallowed by the patient and follows its course passively. However, greater possibilities could emerge if microrobots could be propelled and controlled actively. The solution of using magnetic fields for propulsion is elegant because it externalises the power source and the control system out of the microrobot for greater miniaturisation possibilities. Most applications of magnetic steering for micropropulsion can be classified into one of three modes [3]: (i) an oscillating uniform magnetic field generates an oscillating torque on a magnetic robot which induces a flapping motion [4]; (ii) a rotating field induces a rotation of the robot which is propelled forward by a helical tail; and (iii) a magnetic gradient simply pulls the microrobot.

It is the latter mode of propulsion that was employed to move a ferromagnetic sphere using the magnetic field gradients generated by a clinical magnetic resonance imaging (MRI) scanner in vitro [5] and in vivo [6]. The use of a MRI scanner as a propulsion platform for microrobots offers the possibility to combine actuation and imaging in a single technology already widely available in hospitals [7].

Lalande et al. [8] showed that the magnetic fields generated by a MRI-scanner could be used to propel a swimming microrobot in a fish-like manner. An oscillating transverse magnetic field gradient is employed to pull the ferromagnetic head of the robot fish from left to right in a sway mode while its flexible tail converts this motion into a lift force which generates thrust. This form of actuation is different from previously mentioned modes of magnetic micropropulsion as it is based on an oscillating magnetic gradient rather than an oscillating uniform field as in [4]. MRI scanners can generate fast changing magnetic gradients but cannot modify significantly their permanent magnetic field. An advantage of the new mode of propulsion of [8] is that it could be combined with a conventional pulling mode to lead to a superior forward swimming speed.

The robot fish of Lalande et al. [8] swam the fastest when actuated with the lowest frequencies (0.2 Hz) and the strongest gradients (24 mT/m) tested. However, their robot has one major limitation: it can only swim in one direction. The slightest anisotropy in the ferromagnetic bead used for propulsion gives rise to a preferential magnetisation direction which in turn rotates the untethered robot fish back to its preferred direction along the permanent magnetic field of the scanner.

It is the goal of this paper to present an improved version of the robot fish of Lalande et al. [8] which can swim in any direction at the free-surface of a water bath. Moreover, we seek to identify the important parameters that influence the velocity and the gait of the robot. To this end we present many experimental results on the swimming performance of the new design as well as a dimensional analysis of these results. The paper is organised as follows: the robot fish and the experimental method are described in Section II along with the measured trajectories and velocities in Section III. These results are put in perspective and discussed with a proper dimensional analysis in Section IV before concluding with the avenues of future work in Section V.

II. EXPERIMENTAL METHOD

A photograph of the robot fish is shown in Fig. 1. The head of the fish is made of a chrome-steel ferromagnetic bead of diameter \( d = 8 \) mm with a saturation magnetisation of \( M_s = 1.3 \times 10^6 \) A/m.

The bead is enclosed in a rigid cylindrical casing which allows it to spin freely. This is the main improvement in the robot over that of [8]. In theory, since the bead is spherical and made of a soft ferromagnetic material, it should
where \( V \) can be generated on the bead by applying a magnetic gradient saturation by the permanent field of the scanner. The ferromagnetic bead of the robot fish is magnetised to be used to film the experimental runs.

The vertical (\( z \)) component of the permanent magnetic field (\( \vec{B} \)) is placed in the bore of a 1.5 T Siemens Sonata MR scanner. From Maxwell’s equations, \( \vec{F}_m = V (\vec{M} \cdot \nabla) \vec{B} \),

\[
\begin{align*}
\{ F_{mx} \\ F_{my} \\ F_{mz} \} &= VM_s \{ G_x \\ G_y \\ G_z \} .
\end{align*}
\]

The three set of gradient coils in the MRI scanner can generate the gradients \( G_x, G_y, G_z \) which are normally used for imaging.

The swimming mechanism is illustrated in Fig. 4. For effective thrust generation, the fish must convert the actuation \( F_{mx} \) in the \( x \)-direction into a positive force in the \( z \)-direction. At any instant \( t \), the robot is at an angle \( \theta(t) \) with the \( z \)-direction. In a frame of reference moving with the robot, fluid flows at velocity \( U \) with an angle of attack \( \alpha \). This flow creates forces parallel and normal to its direction, namely the drag force \( F_D \) and the lift force \( F_L \). The forward thrust is produced by the lift force component \( F_L \sin(\theta + \alpha) \) in the forward \( z \)-direction. The robot-fish effectively behaves as an
airfoil towed from side to side.

In the following section, the results presented are obtained from analysis of the video images using ImageJ and Matlab software.

### III. RESULTS

Typical trajectories of the robot fish obtained from manual tracking of the videos are shown in Fig. 5. They are superimposed onto composite photographs of the sequence. It is from trajectory data that the rest of the results are obtained. The amplitude of sway $A$ is measured from peak to peak in $x$. The average velocity $\bar{U}$ is measured along the curved trajectory while $\bar{U}_z$ is the average forward velocity. Moreover, by tracking the position of two points on the robot (the head and the tip of the tail), the angle of yaw $\theta$ can be calculated.

In Fig. 6, the measured position in $x$ as well as the angle $\theta$ are shown in function of time for the same specimen as in Fig. 5 (a). The position is plotted with white circles with respect to the left axis while the angle is plotted with black dots with respect to the right axis. The time series of the angle has the form of a square wave which leads in phase the transverse position time series. The squareness of the angle amplitude wave is explained by the small duty cycle employed $D = 0.1$ and the form of the actuation signal (Fig. 3). The angle varies rapidly during the short application ($t_a = 0.16 s$) of the magnetic gradient and stays almost constant until the next gradient in the opposite direction. The transverse displacement time series is smoother although the robot fish accelerates abruptly upon the application of a gradient. Note that these position and angle traces are typical, although for high actuation frequency the signal is not as clear. That is because at high actuation frequency, the amplitudes are smaller and the sampling rate is limited to the frame rate of the video camera.

In Fig. 7 the amplitude (a) and forward velocity (b) obtained for a series of experiments for varying tail length and gradient amplitude are shown. Each point corresponds to the averaged values obtained over an experimental run of the robot fish crossing the aquarium. In Fig. 7 (a), for the range of gradients studied, the amplitude always increases with the gradient. We can also see that a shorter tail gives rise to larger amplitude: on plot (a) the triangles are above the squares. In Fig. 7 (b), the picture is more complicated. For most specimens, greater gradient values tend to increase the forward velocity, however for the shortest tail (▲), the robot is slower at stronger actuation.

In Fig. 8, the influence of the actuation frequency on the
amplitude (a) and the forward velocity (b) of the robot is shown. On the logarithmic plot, the points of amplitude measurements decrease in a straight line with increasing frequency. On the other hand, for all tail lengths, the forward velocity is maximal at a frequency between 0.3 and 0.4 Hz. An interesting phenomenon happens at the highest frequencies tested as the robot fish swims backwards (the velocities measured are negative at \( f = 2 - 3 \text{ Hz} \)).

The variation of the swimming behaviour of the robot with frequency, magnetic gradient and fish length is rather complex, so to get a better understanding of it we develop a dimensional analysis in the next section.

**IV. Dimensional Analysis and Discussion**

To get a rough estimate of how the dynamics of the swimming robot scales with the magnetic force and the actuation frequency, we can do a simple dimensional analysis of the two important time scales of the problem. The first time scale is the duration of the gradient pulse \( t_a \).

The second one is a little more subtle and comes from hydrodynamics. On top of the lift and drag forces, the water also exerts forces on the robot fish through the added mass. As the robot accelerates, it accelerates part of the surrounding fluid with it [9]. For a flat plate of length \( \ell \) and width \( w \) submerged in a fluid of density \( \rho \), the added mass can be estimated as \( m = \frac{1}{6} \rho \pi w^2 \ell \). For simplicity, we neglect the contribution of the mass of the chrome-steel bead to the rotational inertial of the robot and consider only the fluid added mass. The moment of inertia about the centre of the plate is thus \( I = \frac{1}{12} m \ell^2 = \frac{1}{48} \pi \rho w^2 \ell^3 \). We can then expect the magnetic force to create a rotational acceleration on the robot fish:

\[
I \frac{\partial^2 \theta}{\partial t^2} = \frac{F_{mx} \ell}{2}.
\]  

By integrating twice Eq. 3, we find that the time necessary to reach an arbitrary angle of \( \theta = 1 \) is

\[
t_{\text{hydro}} = \sqrt{\frac{4I}{F_{mx} \ell}} = \sqrt{\frac{\pi \rho}{12 F_{mx}}}. \tag{4}
\]

We can then write the ratio of time scales as

\[
\tau = \frac{t_a}{w \ell} \sqrt{\frac{12 F_{mx}}{\pi \rho}} = \frac{D}{2 f w \ell} \sqrt{\frac{12 V M \rho G_x}{\pi \rho}}. \tag{5}
\]

The dimensionless parameter \( \tau \) thus relates the duration of the gradient pulses to the rotational acceleration time scale.

On Fig. 9, the standard deviation of the angle \( \theta \) the robot fish makes with the \( z \)-axis (a) and the dimensionless amplitude of the trajectory are presented versus the time scale ratio. The standard deviation of \( \theta \) gives us an indication of the fluctuation amplitude in orientation. Note that all the experimental points from the previous section are included in these plots. The dimensionless parameters allow to collapse all experimental points. For all the tests performed, the angular fluctuation amplitude and the dimensionless sway amplitude increase monotonically with \( \tau \) and trends are easily discernible.

The swimming characteristic in which we are most interested is the velocity of the robot fish. We define the total reduced velocity as \( U_R = \bar{U} / f \ell \) which is based on

![Fig. 7: Plots of the total amplitude of the transverse excursion \( A \) (a) and time-averaged forward velocity \( U_z \) (b) of the robot fish in function of the applied transverse magnetic field gradient \( G_x \) for varying tail length: 3 cm (▲); 4 cm (△); 5 cm (△); 6 cm (■); 7 cm (■); 8 cm (□). The frequency is fixed at \( f = 0.20 \text{ Hz} \).](image1)

![Fig. 8: Plots of the total amplitude of the transverse excursion \( A \) (a) and time-averaged forward velocity \( U_z \) (b) of the robot fish in function of the driving frequency \( f \) for varying tail length: 3 cm (▲); 4 cm (△); 5 cm (△); 6 cm (■); 7 cm (■); 8 cm (□). The gradient is fixed at \( G_x = 20 \text{ mT/m} \).](image2)
the average velocity of the fish along its trajectory, while $U_{Rz} = U_z/f\ell$ is based on the forward velocity. In Fig. 10, the total reduced velocity (●) and the forward reduced velocity (○) are shown. Just like the amplitude, the total reduced velocity increases monotonically with $\tau$. However, the forward reduced velocity reaches a plateau at $U_z = 1$ for $\tau$ valued between 2 and 3 and decreases for higher values. Physically what is happening, is that a high values of $\tau$ valued between 2 and 3 and decreases for higher values.

This scaling argument explains why the forward velocity of the shortest specimen (▲) in Fig. 7 decreases for the strongest values of magnetic field gradient. Small length, low frequency and large magnetic gradient lead to a large value of $\tau$ (see Eq. 5). At large values of $\tau$, the robot swims from side to side and is less efficient at converting actuation into forward motion.

As for the backwards swimming observed at high frequency in Fig. 8, it is seen to occur at the lowest values of $\tau$ in Fig. 10. It is not obvious why the robot fish swims backwards at low values of $\tau$. One possible explanation is that a variation of the actuation frequency leads to a phase reversal of the $\theta$ and $x$ degrees of freedom of the robot fish similarly to a periodically excited harmonic system. Another explanation could be that the backwards motion was due to a flexural waves travelling in the tail rather than a solid body rotation like in the regular forward mode of locomotion. This would be consistent with the facts that backwards swimming was only observed for relatively long specimens and in these occurrences, the tail was seen to flex significantly.

From the good collapse of the experimental results in dimensionless form, we can draw conclusions about the parameters of the ideal robot fish. To obtain the fish that swims forward the fastest, we need to keep the value of $\tau$ between 2 and 3 to maximise $U_{Rz}$. With $U_{Rz}$ maximised, $\ell$ and $f$ must also be maximised so that $U_z$ is the largest. To keep $\tau$ within the desirable range, one would thus want to maximise the duty cycle and the magnetic force.

However, for the biomedical applications intended (possibly carrying a camera in the gastrointestinal tract), the sway amplitude is also of concern. If the amplitude $A$ is too large, the robot fish requires too much space to swim. To minimise $A$, the parameter $\tau$ must be minimised and the length $\ell$ of the fish must be maximised.

**V. Conclusion**

A swimming robot actuated by a MR scanner was built and tested. The new concept described here allows the robot to be actuated in any direction in the scanner. The influence of the length of the robot as well sequence parameters were studied. From the parameter study and the dimensional analysis performed here, a better understanding of the swimming mechanism was brought and the important parameters were identified.

The future work on the robot fish concept will focus on miniaturising the robot and improving the actuation sequence.

Through miniaturisation of the robot, the force balance will change. The ratio of the inertial to the viscous forces is very important in the swimming mechanism. This ratio is the Reynolds number defined as

$$Re = \frac{pU\ell}{\mu},$$

where $\mu$ is the fluid dynamic viscosity. In the swimming results presented here, $Re$ varies between 900 and 3600. With a smaller size $\ell$ the Reynolds number decreases. The lift mechanism that generates thrust is inertia-based and cannot work at low Reynolds number. So there is a limit on how small the robot can be made. However that small $Re$ limit...
is still far and we believe that upon using a more effective sequence and a more streamlined robot fish design, a higher swimming speed can be achieve. A higher $\bar{U}$ could partly compensate for a lower value of $\ell$ in keeping the Reynolds number large enough.

A photograph of the current robot design compared with the next generation is shown in Fig. 11. The new design is shaped after an airfoil section. The solid acrylic airfoil contains two cavities: a cylindrical one close to the head containing the ferromagnetic bead and allowing it to spin, and a second one in the middle of the body filled with air to give an overall slightly positive buoyancy to the robot fish.

On top of miniaturising the robot and improving its design, work has to be done on the propulsion sequence. With a clinical scanner, the gradient amplitude cannot be increased much beyond what was tested here. MRI scanners cannot hold large gradients with a large duty cycle for a long period of time. There is thus a trade-off between duty cycle and hold large gradients with a large duty cycle for a long period much beyond what was tested here. MRI scanners cannot

For even better performances, the propulsion sequence will have to undergo another modification. That is, the next generation sequence should combine the gradient oscillating from side to side with a simple forward pulling gradient. Considering the limited gradient amplitude and duty cycle the coils of a scanner can hold, the advantage of this combined actuation scheme is that two sets of orthogonal coils at a time are used for propulsion.

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