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TOWARDS A MULTI-FLAGELLA ARCHITECTURE FOR E.COLI INSPIRED SWIMMING MICROROBOT PROPULSION

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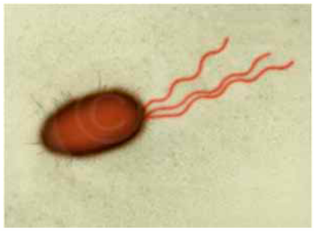
ABSTRACT

One of the primary goals of medical micro and nano robots is to reach currently inaccessible areas of the human body and carry out a host of complex operations, such as minimally invasive surgery (MIS), highly localized drug delivery, and screening for diseases at their very early stages. One of the innovative approach to design microrobot propulsion is based on the flagellar motion of bacteria [1]. Certain bacteria, such as Escherichia coli (E.coli) use multiple flagella often concentrated at one end of their bodies to induce locomotion. Each flagellum is formed in a left-handed helix and has a motor at the base that rotates the flagellum in a corkscrew motion. As pointed out by Purcell [2], microorganisms experience an environment quite different from our own. In particular, because of their small size (of the order of microns), inertia is, to them, essentially irrelevant. The fact that inertia is irrelevant for micro-organisms makes it difficult for them to move. The propulsive mechanisms based on flow inertia will not work on a mesoscopic scale. To overcome this problem, organisms living in low Reynolds number regimes have developed moving organelles which have a handedness to them. For instance, E. Coli's flagella rotate with a helical motion, much like a corkscrew. This configuration produces patterns of motion that do not repeat the first half of the cycle in reverse for the second half, allowing the organisms to achieve movement in their environment. In this Paper, The multi-flagella propulsion system with separate motor for each flagellum is investigated using stokeslet and rotlet theory[3,4]. The fluid dynamics in problems of microorganism motion and microrobots, where length and velocity scales are very small, is well-modeled by the Stokes equations for incompressible flows:



E. coli photo

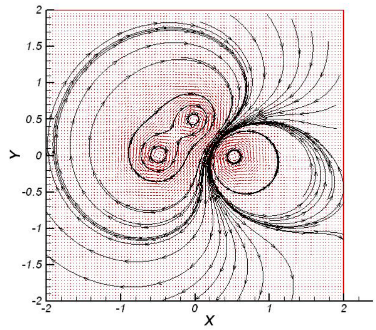
$$0 = -\nabla \tilde{P} + \mu \Delta \tilde{U} + \tilde{f} \quad , \quad 0 = \nabla . \tilde{U}$$

The rigid (not flexible) multi-flagella dynamic is modeled by forces applied on the flagella points and by a torque at the base of each using regularized stokeslet and rotlet theory [3,4]. The regularized 3D stokeslet and rotlet solution is given by:

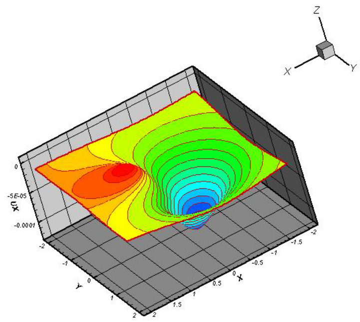
$$U = \sum_{i=1}^{N_f} U_r(x; x_{n_i}, L_i) + \sum_{j=1}^{N_x} U_s(x; x_j, f_j)$$

This formula expresses analytical solutions to a regularized version of the Stokes equations in which the forces and torques are not applied at single points, but are distributed over a small neighborhood of the application point [4]. This closed form solutions give us a velocity field that can be used to track particles moving in the fluid. For flow field simulation by stokeslet and rotlet, the forces are estimated by RFT theory

and new approach of "local corrected velocity" which uses the velocity field of previous iteration to calculate the normal and tangential velocities when the helical structure rotates. This way considers the effects of neighbor flagella in calculations. By this approach, we investigate the effects of flagella shape parameters such as amplitude of each flagellum, wavelength of the flagellum,…and angular velocities (with its direction) of each flagellum on overall flow field around the robot and on the robot net forces and robot net moments. Right figures show the flow field produced by three flagella (two clockwise and one counter-clockwise). After velocity field calculation, we use the velocity field to calculate the overall force and moment which is applied on the robot in three directions: $f_x, f_y, f_z, M_x, M_y, M_z$. For trajectory and propulsion control of the swimming robot, first of all, designer should know the relation between the forces and moments and angular velocities of the flagella to adjust the rotation rates of the motorsfor a given required loading. So we have designed a multi-layer perceptron neural network (MLPR) with one hidden layer and employed to estimate the angular velocities of the motors for a given $f_x, f_y, f_z, M_x, M_y, M_z$. For ANN training, the results of the computational code (which uses the stokeslet and rotlet theory as described before) for different angular velocity combinations include positive and negative of rotations and multi-flagella parameters like number of flagella (N), etc. are used. The results indicate good agreement between the ANN predictions and the computational code. The below table shows a comparison between ANN predictions (for the case with given $f_x, f_y, f_z, M_x, M_y, M_z$) and the exact values with the same loading (generated by the code). So the trained ANN can be used to adjust the angular velocities of the robot flagella to achieve the required forces and moments for tracking a trajectory.



Velocity field viewed from behind the robot for N=3


Axial velocity viewed from behind the robot for N=3

Angular Velocity	$w_1(hz)$	$w_2(hz)$	$w_3(hz)$
Computational Code	-800	-800	800
ANN Results	-801.128	-799.83	799.89

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