

Biosensing and Actuation for Microbiorobots

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One of the great challenges in nano/micro scale science and engineering is the independent manipulation of cells and man-made objects with active sensing. For such work, there is a need for controllable actuators. Actuation can be realized using inorganic components; however, these systems are expensive to produce and require sophisticated fabrication techniques. Furthermore, they do not have integrated biosensing elements which will be important in future applications. Using biomolecular motors is another option, but these systems are difficult to employ when isolated from the supporting cells. As an alternative solution, previous studies explored different forms of actuation and control with microorganisms. Bacteria, in particular, offer several advantages as controllable microactuators: they draw chemical energy directly from their environment, they are genetically modifiable, and they are scalable and configurable in the sense that any number of bacteria can be selectively patterned. Additionally, the study of bacteria inspires inorganic schemes of actuation and control. For these reasons, we chose to employ bacteria while controlling their motility using optical and electrical stimuli.

MBRs are negative photosensitive epoxy (SU8) microfabricated structures with typical feature sizes ranging from 1-100 μm coated with a monolayer of the swarming *Serratia marcescens*. The adherent bacterial cells naturally coordinate to propel the microstructures in fluidic environments which we call Self-Actuation. First, we demonstrated the control of MBRs using self-actuation, DC electric fields and ultra-violet radiation and develop an experimentally validated mathematical model for the MBRs [1], [2]. This model allows us to to steer the MBR to any position and orientation in a planar micro channel using visual feedback and an inverted microscope. Examples of sub-micron scale transport and assembly as well as computer-based closed-loop control of MBRs were presented. We demonstrated experimentally that vision-based feedback control allows a four-electrode experimental device to steer MBRs along arbitrary paths with micrometer precision. At each time instant, the system identifies the current location of the robot, a control algorithm determines the power supply voltages that will move the charged robot from its current location toward its next desired position, and the necessary electric field is then created.

Second, we developed biosensors for the MBRs. Microscopic devices with sensing capabilities could significantly improve single cell analysis, especially in high-resolution detection of patterns of chemicals released from cells in vitro. Two different types of

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sensing mechanisms are employed. The first method is based on harnessing bacterial power, and in the second method we use genetically engineered bacteria [3]. The small size of the devices gives them access to individual cells, and their large numbers permit simultaneous monitoring of many cells.

This work is a step toward in vitro manipulation of cells as well as controlled assembly of micro-components. MBRs can be used as building blocks for more sophisticated functional micro-devices in the micro-bio interface. Additional controllability can be introduced by modifying the material properties of SU8. As a proof-of-concept, we fabricated magnetically-responsive MBRs by using a ferromagnetic photoresist, which, in turn, was prepared by suspending iron oxide nanoparticles in SU8. These truly micron-sized, biocompatible ferromagnetic microtransporters were fabricated using a simple, single step fabrication method and can be produced in large numbers. We demonstrated that they can be navigated to separate single cells with micron-size precision without disturbing the local environment [4].

Our techniques can be used to fabricate, calibrate and transport MBRs in microfluidic channels in a controllable fashion. The paradigm introduced here can easily be scaled down and can be integrated with other microelectromechanical systems (MEMS) technologies. Our future work will also address the integration of biosensing and bio-actuation onboard the MBR.

REFERENCES

- [1] A. A. Julius, M. S. Sakar, E. Steager, U. K. Cheang, M. J. Kim, V. Kumar, and G. J. Pappas, "Harnessing bacterial power in microscale actuation," in *Proceedings 41st IEEE Conf. Robotics and Automation*, Japan, May 2009.
- [2] M. S. Sakar, E. B. Steager, D. H. Kim, A. A. Julius, M. J. Kim, V. Kumar, and G. J. Pappas, "Biosensing and actuation for microbiorobots," in *Proceedings 42nd IEEE Conf. Robotics and Automation*, Alaska, May 2010.
- [3] M. S. Sakar, E. B. Steager, D. H. Kim, M. J. Kim, G. J. Pappas, and V. Kumar, "Mobile hybrid microdevices for biosensing," *Appl. Phys. Lett.*, vol. (in review), 2010.
- [4] ———, "Single cell manipulation using ferromagnetic composite microtransporters," *Appl. Phys. Lett.*, vol. 96, p. 043705, 2010.