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14. ABSTRACT Although nano- and microfabrication techniques are rapidly advancing, it remains a challenge to fabricate separate individual microscale actuators and sensors en masse. A possible resource for such tiny elements exists within microorganisms. Specifically, the abilities of bacteria to move in a self-propelled manner and to detect and process sensory information represent enormous potential that can be harnessed and integrated into microscale robotics and biosensor systems. The objective of the proposed program is to develop a platform that integrates bacteria with enhanced motility and signaling behavior (through synthetic biology) into a microscale sensing and robotic system.					
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Report Title

Final Report: Microbiorobots for Manipulation and Sensing

ABSTRACT

Although nano- and microfabrication techniques are rapidly advancing, it remains a challenge to fabricate separate individual microscale actuators and sensors en masse. A possible resource for such tiny elements exists within microorganisms. Specifically, the abilities of bacteria to move in a self-propelled manner and to detect and process sensory information represent enormous potential that can be harnessed and integrated into microscale robotics and biosensor systems. The objective of the proposed program is to develop a platform that integrates bacteria with enhanced motility and signaling behavior (through synthetic biology) into a microscale sensing and robotic system. The platform, termed microbiorobots (MBRs), consists of controllable, reconfigurable elements of a microscale sensing and transportation network in biofactory-on-a-chip systems. The goal of this collaborative proposal, initiated at Drexel University with the participation of Rensselaer Polytechnic Institute, is to use multiple types of bacteria, which can be roughly categorized into two functional types, propulsion/actuation and sensing/computation, to enhance the capabilities of existing microrobots through localized sensing and computation. In pursuit of this goal, we use synthetic biology to engineer microbes capable of sensing chemicals or other environmental cues and tuning their motility. In addition we use intercellular communication to further coordinate the microbial populations. The use of bacteria as bio-info-micro systems represents a critical step toward both how microbiorobotics can be introduced as a tool in nano/microscale engineering work as well as how scientists and engineers can learn from nature using modern fabrication, genetic manipulation, and deterministic and stochastic modeling and control. This platform will be applicable in microscale assembly systems and biosensors that require autonomous coordination of bacteria.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
04/19/2016 23.00	Hoyeon Kim, MinJun Kim. Electric field control of bacteria-powered microrobots (BPMs) using static obstacle avoidance algorithm, IEEE TRANSACTIONS ON Robotics, (02 2016): 125. doi:
08/27/2013 4.00	Min Jun Kim, Anak Agung Julius, Dal Hyung Kim, Paul Kim, Yan Ou. Motion control of magnetizedTetrahymena pyriformis cells by amagnetic field with Model PredictiveControl, International Journal of Robotics Research, (01 2013): 129. doi:
10/08/2015 16.00	Aaron Becker, Yan Ou, Anak Agung Julius, Min Jun Kim, Paul Seung Soo Kim. Imparting magnetic dipole heterogeneity to internalized iron oxide nanoparticles for microorganism swarm control, Journal of Nanoparticle Research, (03 2015): 0. doi: 10.1007/s11051-014-2746-y
10/08/2015 17.00	U. Kei Cheang, Min Jun Kim. Self-assembly of robotic micro- and nanoswimmers using magnetic nanoparticles, Journal of Nanoparticle Research, (03 2015): 0. doi: 10.1007/s11051-014-2737-z
10/08/2015 18.00	Hoyeon Kim, Jamel Ali, Kiran Phuyal, Sungsu Park, Min Jun Kim. Investigation of bacterial chemotaxis using a simple three-point microfluidic system, BioChip Journal, (03 2015): 0. doi: 10.1007/s13206-014-9107-x
10/08/2015 19.00	U Kei Cheang, Farshad Meshkati, Dalhyung Kim, Min Jun Kim, Henry Chien Fu. Minimal geometric requirements for micropropulsion via magnetic rotation, Physical Review E, (09 2014): 0. doi: 10.1103/PhysRevE.90.033007
10/08/2015 15.00	Hoyeon Kim, U Kei Cheang, Dalhyung Kim, Jamel Ali, Min Jun Kim. Hydrodynamics of a self-actuated bacterial carpet using microscale particle image velocimetry, Biomicrofluidics, (03 2015): 0. doi: 10.1063/1.4918978
10/08/2015 14.00	U Kei Cheang, Kyoungwoo Lee, Anak Agung Julius, Min Jun Kim. Multiple-robot drug delivery strategy through coordinated teams of microswimmers, Applied Physics Letters, (08 2014): 0. doi: 10.1063/1.4893695
TOTAL:	8

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u>	<u>Paper</u>
08/27/2013	3.00 Kiran Phuyal, MinJun Kim. Mechanics of swimming of multi-body bacterial swimmers using nonlabeledcell tracking algorithm, Physics of Fluids, (01 2013): 11901. doi:
TOTAL:	1

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>	<u>Paper</u>
TOTAL:	

Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u>	<u>Paper</u>
08/27/2013 5.00	Yan Ou, Paul Kim, Min Jun Kim, Anak Agung Julius, Aaron Becker. Feedback Control of Many MagnetizedTetrahymena pyriformis Cells by Exploiting Phase Inhomogeneity, IEEE/RSJ International Conference on Intelligent Robots and Systems. 03-NOV-13, . : ,
09/15/2014 10.00	Paul Kim, Aaron Becker, Yan Ou, Agung Julius, Min Jun Kim. Swarm control of cell-based microrobots using a single global magnetic field, International Conference on Ubiquitous Robots and Ambient Intelligence. 30-OCT-13, . : ,
09/15/2014 11.00	Hoyeon Kim, U Kei Cheang, Kyoungwoo Lee, Min Jun Kim. Obstacle Avoidance Method for MicroBioRobots Using Electric Field Control, the 4th Annual IEEE International Conference on CYBER Technology in Automation, Control, and Intelligent Systems (IEEE-CYBER 2014). 04-JUN-14, . : ,
09/15/2014 9.00	Aaron Becker, Yan Ou, Paul Kim, Min Jun Kim, Agung Julius. Feedback control of many magnetized Tetrahymena pyriformis cells by exploiting phase inhomogeneity, IEEE/RSJ International Conference on Intelligent Robots and Systems. 03-NOV-13, . : ,
10/08/2015 22.00	U Kei Cheang, Dejan Milutinovic, Jongeun Choi, Min Jun Kim. TOWARDS MODEL-BASED CONTROL OF ACHIRAL MICROSWIMMERS, the ASME 2014 Dynamic Systems and Control Conference. 22-OCT-14, . : ,
10/08/2015 21.00	Hoyeon Kim, U Kei Cheang, Anak Agung Julius, Min Jun Kim. Dynamic Obstacle Avoidance for Bacteria-Powered Microrobots, IEEE/RSJ International Conferenceon Intelligent Robots and Systems. 28-SEP-15, . : ,
10/08/2015 20.00	Yan Ou, Peter Kang, Min Jun Kim, Anak Agung Julius. Algorithms for Simultaneous Motion Control of Multiple T. PyriformisCells: Model Predictive Control and Particle Swarm Optimization, IEEE International Conference of Robotics and Automation . 26-MAY-15, . : ,
TOTAL:	7

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received

Paper

08/29/2012 2.00 MINJUN KIM, KIRAN PHUYAL. Mechanics of Swimming of Multi-body Bacterial Swimmers Using Non-Labeled Cell Tracking Algorithm, Physics of Fluids (05 2012)

09/15/2014 8.00 Kyoungwoo Lee, Anak Agung Julius, Min Jun Kim, U Kei Cheang. Multiple-robot drug delivery strategy through coordinated teams of microswimmers, APPLIED PHYSICS REVIEWS (08 2014)

09/15/2014 7.00 Dal Hyung Kim, , Paul Seung Soo Kim, Kyoungwoo Lee, JinSeok Kim, Min Jun Kim. Galvanotactic behavior of Tetrahymena pyriformis under electric fields, Journal of Micromechanics & Microengineering (08 2013)

TOTAL: 3

Number of Manuscripts:

Books

Received

Book

08/29/2012 1.00 MINJUN KIM, A. AGUNG JULIUS, EDWARD STEAGER. Microbiorobotics: Biologically Inspired Microscale Robotic Systems, London: Elsevier, (05 2012)

TOTAL: 1

Received

Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Prof. Kim has been selected to receive the prestigious 2016 Netexplo Award for his work with micro-swimmer robots. Since 2008, based on a panel vote participated in by over 200 experts and business professionals from around the world, UNESCO and Netexplo have announced annually the Netexplo 100, a selection of the 100 most promising digital initiatives. From these, the ten most exceptional, innovative and promising projects are selected as award winners and presented at the Netexplo Forum in Paris. From these ten, a final Grand Prix 2016 award is selected.

Netexplo is an independent observatory that studies the impact of digital technology on society and business. Created in 2007 by Martine Bidegain and Thierry Happe in partnership with the French Senate and the French Ministry for the Digital Economy, Netexplo takes a unique approach to understanding digital society. Through its International University Network, the Netexplo Observatory scans the world for the new faces of tech and their inventions. The founding partners, the Senate, the Ministry for the Digital Economy and HEC Paris business school share with Netexplo a commitment to covering every aspect of digital innovation, whether technological, commercial, organizational, social or environmental.

Dr. Kim's research is with tiny swarming robots that have the potential of swimming through a person's arteries to detect and clear blockages or to deliver a drug to a precise area of the body. As an award winner, he presents his work on February 10, 2016 at Paris-Dauphine University, Paris.

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
HOYEON KIM	1.00	
KIRAN PHYUAL	0.50	
ADAM G.W. BOWER	0.50	
PAUL SEUNGSOO KIM	1.00	
JAYAMARY DIVYA RAVICHADNI	1.00	
U KEI CHEANG	0.25	
FTE Equivalent:	4.25	
Total Number:	6	

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FARAH TENGRA	0.25
FTE Equivalent:	0.25
Total Number:	1

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
MINJUN KIM	1.00	
CYNTHIA COLLINS	0.50	
ANAK AGUNG JULIUS	0.50	
FTE Equivalent:	2.00	
Total Number:	3	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	Discipline
DAMIEN TURCHI	0.25	Mechanical Engineering
LOUIS ROGOWSKI	0.45	Mechanical Engineering
ALEXANDRA DEAL	0.30	Biosciences
FTE Equivalent:	1.00	
Total Number:	3	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 3.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 3.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 2.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 2.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:..... 0.00

Names of Personnel receiving masters degrees

<u>NAME</u>
ADAM G.W. BOWER
Total Number:

1

Names of personnel receiving PHDs

<u>NAME</u>
PAUL SEUNGSOO KIM
HOYEON KIM
Total Number:

2

Names of other research staff

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

We have successfully developed a platform that integrates bacteria with enhanced motility and signaling behavior into a microscale sensing and robotic system. The platform, termed microbiorobots (MBRs), consists of controllable, reconfigurable elements of a microscale sensing and transportation network in biofactory-on-a-chip systems. Physically, our MBRs are fabricated microscale chips with bacterial cells attached to their surface. The MBRs are made of materials with neutral buoyancy, thus enabling us to suspend them in a fluidic working environment.

1. We use synthetic biology to harness and improve not only the motility behavior of the bacteria, but also their sensory, biochemical signaling, and information processing capabilities.
2. By integrating these capabilities with the motility behavior of the bacteria, we can achieve autonomous coordination of the microbiorobots, without external signaling mechanisms. Therefore, our proposed system is controllable in the conventional way (i.e. by using external signaling), as well as through local, internal signaling or autonomous coordination.

We have used multiple types of bacteria that can be roughly categorized into two functional types, propulsion/actuation and sensing/computation. In pursuit of this goal, we have developed synthetic biology to engineer microbes capable of sensing chemicals or other environmental cues and tuning their motility. In addition, we have used intercellular communication to further coordinate the microbial populations. The use of synthetic biology allows us to build systems that can be easily tuned and manipulated, providing an experimental system where we have the unique ability to adjust a variety of parameters. The propulsion/actuation functionality is provided by swimming, flagellated bacteria that deliver propulsive forces for the MBRs. The sensing/computation functionality is provided by genetically engineering bacteria cells that contain novel synthetic genetic networks that enable them to sense and produce various types of small signal molecules. These small signal molecules are used as tokens of information that can be processed with appropriate synthetic networks. The sensing and computation capabilities of the bacteria have been used in autonomous coordination of the MBRs and in their utilization as biosensors.

Fundamental scientific progresses addressed by this research program include (i) the use of synthetic biology in hybrid microrobotics, (ii) obtaining answers to basic questions regarding methods for control input generation using external stimuli that lead to vision-based feedback control of MBRs, (iii) the possibility of using cell-cell communication for coordinated, population level behaviors to achieve biosensing and swarm control of MBRs, thus enabling an entirely new class of sensing and actuation systems. The ability to complete this all at the microscale enables the realization of miniaturized biofactories whose applications are limited only by our imagination but include in vitro precision drug delivery and chemical sensors, each of which has its own needs. Given the still embryonic state of microbiorobotics, any significant progress toward the control of genetically modified engineered bacteria has great impact.

Technology Transfer

N/A

Autonomous Motion Control of Bacteria Powered Microrobots Using Electric Fields

Ph.D Thesis Defense

April 1th, 2016

Hoyeon Kim

Advisor : Prof. Min Jun Kim

Biological Actuation, Sensing & Transport Laboratory
Mechanical Engineering and Mechanics
Drexel University



CONTENTS



I. Introduction

- Motivation
- Reviews
- Objective

II. Research works

- Hydrodynamics of Bacterial carpet using μ PIV
- Static Obstacle Avoidance for Bacteria Powered Microrobots
- Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

IV. Future Works

V. Achievements

CONTENTS



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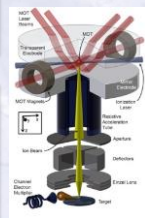
V. Achievements

3

Motivation

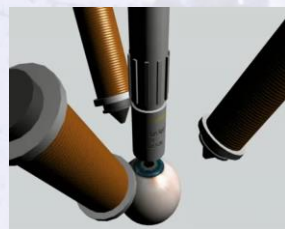


• MEMS



• FIB equipment

▪ Potential tasks

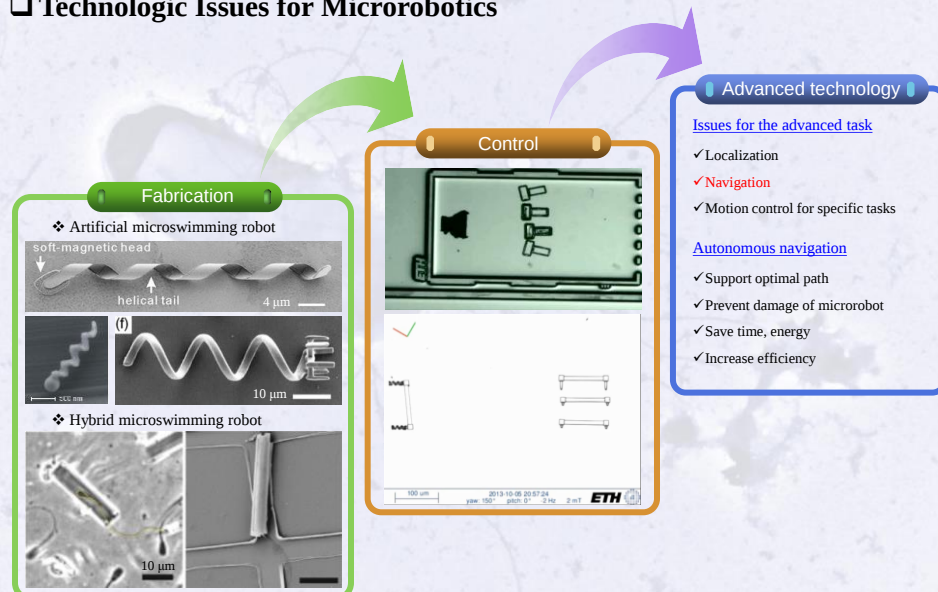


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Motivation



❑ Technologic Issues for Microrobotics



Ghosh 2009 Floyd 2008 Zhang 2009 Ghosh 2009

ETH at 2010 NIST Mobile Microrobotics Challenge, T.Y Hung, 2014.

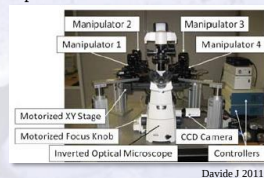
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Reviews

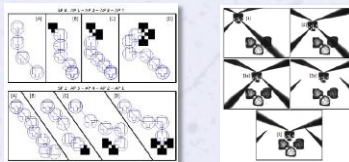


❑ Autonomous motion control for navigation

1. Micromanipulation



Davide J 2011

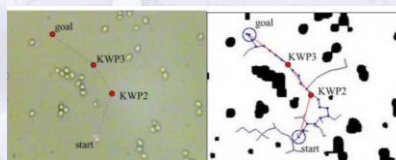


• Microassembly test result using A*

2. Optical Tweezer

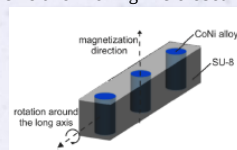


Tao J. 2011

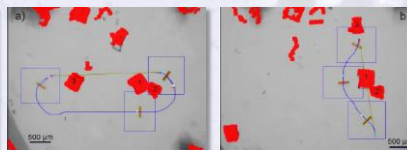


• Cell transportation using RRT

3. Magnetic field for Rolling microrobot



Samuel C. 2015



• Motion planning using RRT

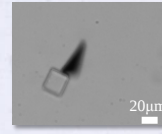
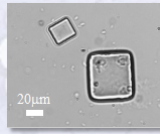
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Objectives



- An autonomous navigation algorithm using Bacteria Powered Microrobots

1. Static obstacle avoidance
2. Dynamic obstacle avoidance



- Collision with static obstacle
- Collision with dynamic obstacle

- Hydrodynamics of bacterial carpet under boundary effect
 1. Visualize the flow field using μ PIV
 2. Analyze the flow field with bounded and unbounded condition

7

CONTENTS



I. Introduction

- Motivation
- Reviews
- Objective

II. Research works

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- Static Obstacle Avoidance for Bacteria Powered Microrobots
- Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

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8

Bacteria Powered Microrobots



□ Introduction of Bacteria Powered Microrobots (BPMs)

• Concept of BPM

• Flagellum motor



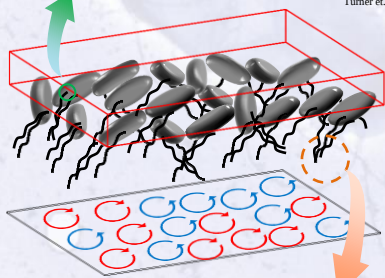
• Swimming motion of bacteria



Turner et al., 2000

Characteristics of Bacteria in Swimming

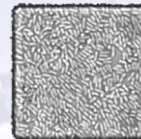
- ✓ 3D motion in fluids
- ✓ 3 – 5 peritrichous flagella
- ✓ Flagella bundle when all motors turn CCW
- ✓ When motors turn CW, bacteria tumble
- ✓ Average swimming velocity: 12 – 50 $\mu\text{m/s}$
- ✓ Random walk



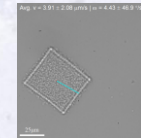
Inorganic body (SU-8 structure)

Biomolecular actuator of bacterial carpet (*Serratia marcescens*)

• Example of BPM

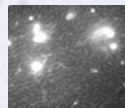


• Self-actuation of BPM



Collective Motion of Flagella

- ✓ Local fluid flow motion
- ✓ Large global coordination due to hydrodynamic interaction
- ✓ A net thrust on the microstructure causing rotational and/or translational movement



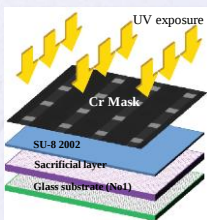
Kim 2009

9

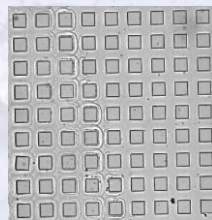
Bacteria Powered Microrobots



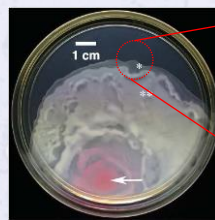
□ Fabrication of Bacteria Powered Microrobots



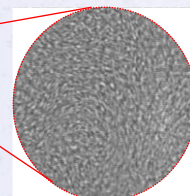
• Fabrication of microstructure



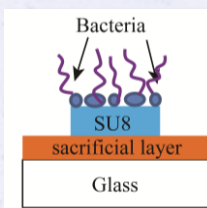
• Release microstructure by Dextran layer



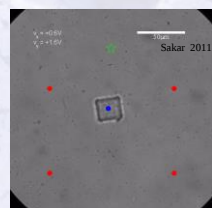
• Swarming agar plate (*Serratia marcescens*)



Steiger et al., 2008



• Scheme of a BPM



• Electrophoretic control

Advantage of biological microrobots

- ✓ Draw energy from fluid
- ✓ Easily manufactured
- ✓ Self-coordinated (quorum sensing or hydrodynamics)
- ✓ Fully controllable due to negative charge in body
- ✓ Adjust orientation of microrobots

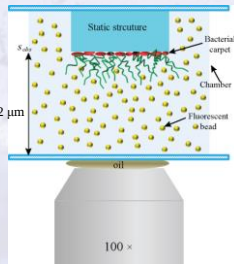
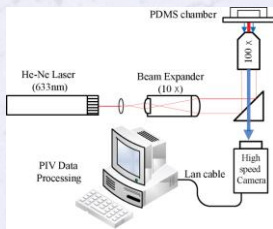
10

I Hydrodynamics of Bacterial carpet

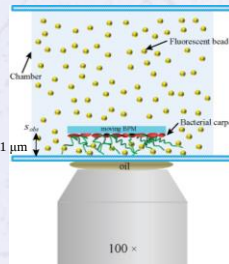


□ Propulsive force by bacterial carpet

1. System setup

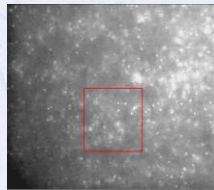


• Tethered structure



• Untethered structure (Self-actuation of BPM)

- **μPIV setup**
 - Laser : 633 nm He-Ne laser
 - Fluorescent bead size : 0.2 μm diameter
 - Camera : High speed camera 250 fps
 - Objective lens : 100 ×
- **Tethered structure**
 - Dimension : 32 × 34 μm²
 - Thickness : 35 μm using SU-8 2035
- **Untethered structure (BPM)**
 - Dimension : 32 × 34 μm²
 - Thickness : 3 μm using SU-8 2002
- **Observed planes**
 - Untethered case : 12 planes (0~22 μm)
 - Tethered case : 1 plane (1 μm)



• Tethered case



• Untethered case

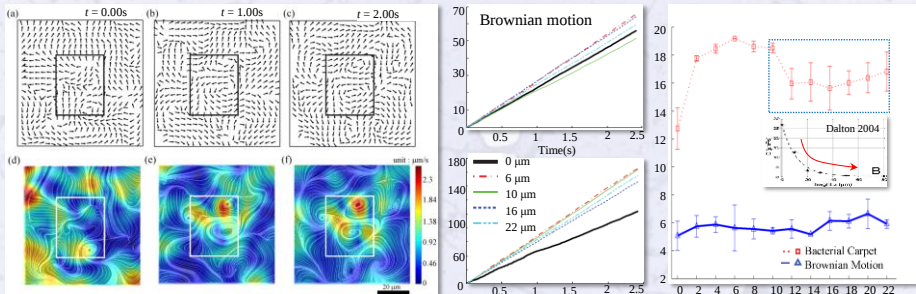
11

I Hydrodynamics of Bacterial carpet



□ Propulsive force by bacterial carpet

2. Experimental results : Tethered structure cases



• Flow field tethered structure (at 6 μm height from bacterial carpet)

• MSD (μm²) comparison

• Diffusion coefficient comparison

▪ Results summary

- There are variance on Brownian motion due to measurement noise.
- The bacterial carpet generates much stronger flow field than Brownian motion.
- The strongest flow is generated at 6~8 μm height from the bacterial carpet.
- The flow field is not decreasing dramatically like 'Dalton paper'.
- The bounded condition (less than 80 μm distance with boundary) affect the flow fields on more than 12 μm height.

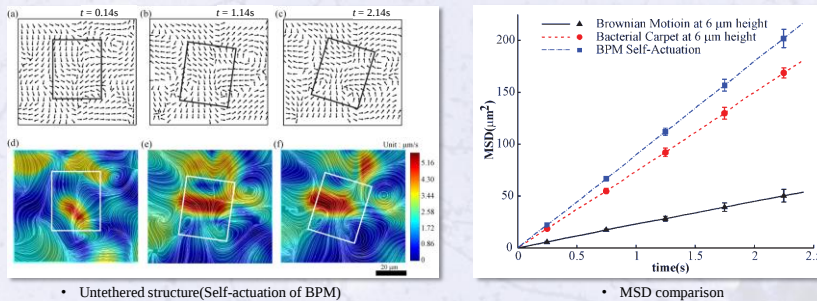
12

I Hydrodynamics of Bacterial carpet



□ Propulsive force by bacterial carpet

3. Experimental results : Untethered structure cases



■ Results summary

- The bacterial carpet was close to wall and boundary effects on the flagella-induced flow field must be taken into account.
- The bacteria secreted lubrication layer, a thin layer of liquid, approximately 1 μm in depth, separates the bacterial carpet from the glass substrate.
- The strong velocity flow profile was observed above the middle of the moving BPM.
- The strong streams of flow were much stronger in the moving BPM than the same area on the static structure surface.
- The MSD of the untethered BPM is larger than the tethered cases by 36.3 μm^2 .

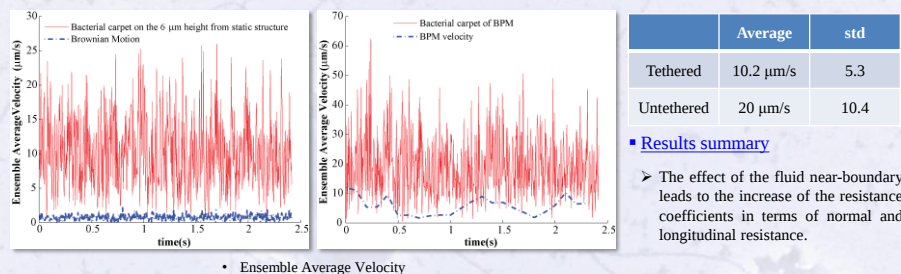
13

I Hydrodynamics of Bacterial carpet



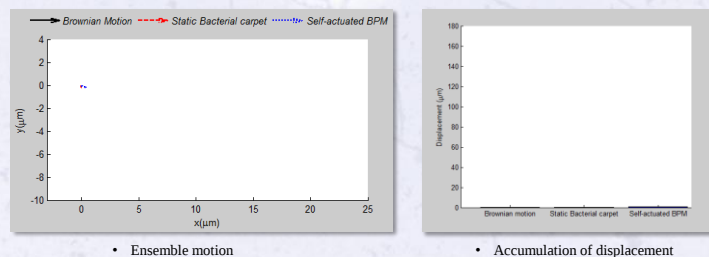
□ Propulsive force by bacterial carpet

4. Comparison of ensemble velocity



■ Results summary

- The effect of the fluid near-boundary leads to the increase of the resistance coefficients in terms of normal and longitudinal resistance.



14



I. Introduction

- Motivation
- Reviews
- Objective

II. Research works

- Hydrodynamics of Bacterial carpet using μ PIV
- Static Obstacle Avoidance for Bacteria Powered Microrobots
- Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

IV. Future Works

V. Achievements

15

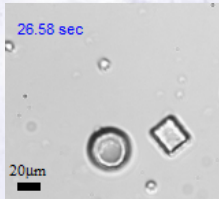
II Static Obstacle Avoidance



□ Constraint elements for obstacle avoidance using BPMs

1. Self-actuation of BPMs

■ Uncontrollable motion

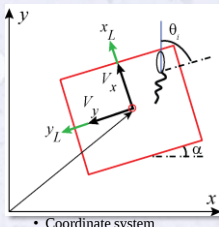


• Collision with obstacle

[High probability of collision risk](#)

- ✓ Inherent motion of BPMs caused by bacterial carpets
- ✓ Uncontrollable motion by electric fields
- ✓ The resultant locomotion by self-actuation and electrophoretic motion

■ Kinematic model of self-actuation BMP



• Coordinate system

- Self-actuation velocities

$$V_x = \bar{p}\beta_1, V_y = \bar{p}\beta_2, \alpha = \bar{p}\beta_3$$

$$\beta_1 := \left(\frac{1}{k_t}\right) \sum_{i=1}^{N_b} \cos\theta_i \quad \beta_2 := \left(\frac{1}{k_t}\right) \sum_{i=1}^{N_b} \sin\theta_i$$

$$\beta_3 := \left(\frac{1}{k_r}\right) \sum_{i=1}^{N_b} (b_{ix} \sin\theta_i - b_{iy} \cos\theta_i)$$

16

II Static Obstacle Avoidance



□ Constraint elements for obstacle avoidance using BMPs

1. Self-actuation of BMPs

- Global coordinate system for position of BMPs

$$V_{gx} = V_x \cos \theta - V_y \sin \theta$$

$$V_{gy} = V_x \sin \theta + V_y \cos \theta$$

$$\Delta d_x = \beta_4 U_x$$

$$\Delta d_y = \beta_4 U_y$$

where, $V_x = \bar{p}\beta_1$, $V_y = \bar{p}\beta_2$, $\alpha = \bar{p}\beta_3$, β_4 : Electrophoretic property

$\bar{p}$: mean propulsive force (0.41pN).

- Kinematic model of BMP's locomotion

$$p_i = p_{i-1} + \text{Locomotion}_{\text{self-actuation}} + \text{Locomotion}_{\text{electrokinetic}}$$

$$\begin{pmatrix} x_i \\ y_i \\ \theta_i \end{pmatrix} = \begin{pmatrix} x_{i-1} \\ y_{i-1} \\ \theta_{i-1} \end{pmatrix} + \bar{p} \begin{bmatrix} \cos \theta_{i-1} & -\sin \theta_{i-1} & 0 \\ \sin \theta_{i-1} & \cos \theta_{i-1} & 0 \\ 0 & 0 & \alpha \end{bmatrix} \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix} t_s + \begin{pmatrix} U_x \\ U_y \\ 0 \end{pmatrix} \beta_4 t_s$$

Unit: $\beta_1, \beta_2: \frac{\mu\text{m}}{\text{spN}}$, $\beta_3: \frac{\text{rad}}{\text{spN}}$, $\beta_4: \frac{\mu\text{m}}{\text{sVcm}}$ 17

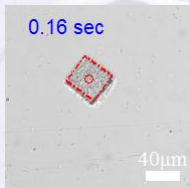
II Static Obstacle Avoidance



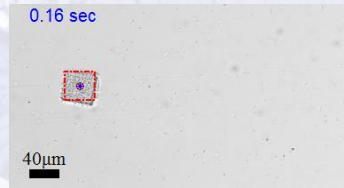
□ Constraint elements for obstacle avoidance using BMPs

2. Reliability of kinematic model

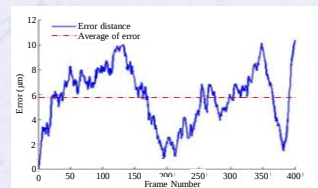
- Modeling Validation using $40 \times 43 \mu\text{m}^2$



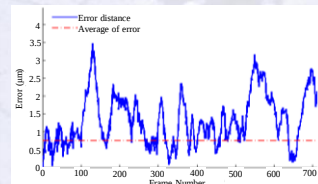
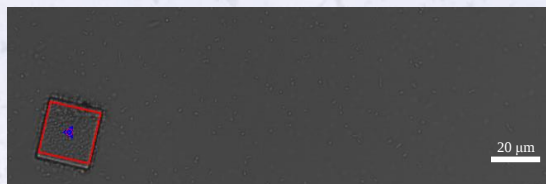
• Self-actuation



• Motion with +20 V/cm (right direction)



- Modeling Validation using $20 \times 23 \mu\text{m}^2$



II Static Obstacle Avoidance

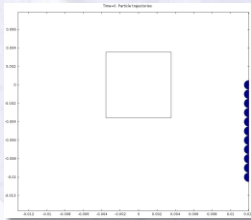


□ Constraint elements for obstacle avoidance using BPMs

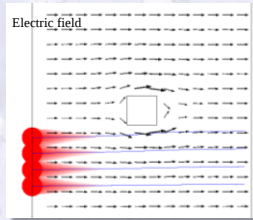
3. Distorted electric field around obstacles

- Unmatched movement with desired motion
 - COMSOL Simulation Setup : Particle is negative charged particle. (9.1×10^{-17} kg, -1.6021×10^{11} C), Obstacle is regarded as insulator, Input - Anode (Left), Cathode (Right) with 10 V/cm

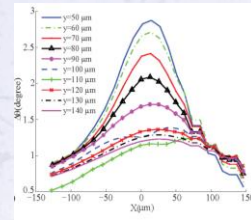
• Particle motion



• Result of Particle trajectories



• The difference of heading angle



▪ Simulation Summary

- ✓ There exist zero potential area around the obstacle which gives non-mobility to the particle.
- ✓ The deformed electric field steers the particle toward the distorted angle. (Maximum 3°)
- ✓ As far away from obstacles, the effect of distorted electric field becomes week.

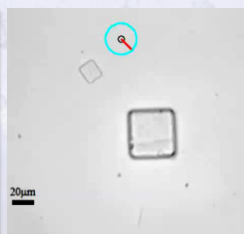
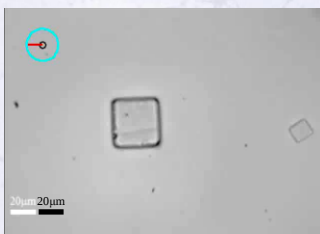
19

II Static Obstacle Avoidance

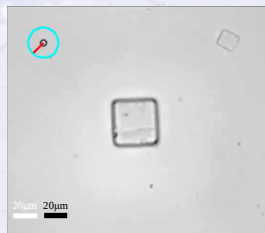
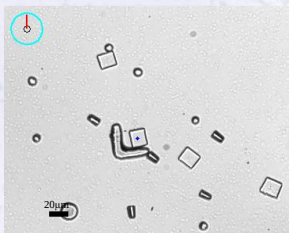


□ Constraint elements for obstacle avoidance using BPMs

4. The effect of distorted electric field



: Electric field direction



▪ Demonstration Result

- ✓ BPM cannot move at zero potential area.
- ✓ BPM follows the deformed electric field.

20

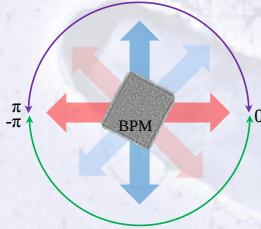
II Static Obstacle Avoidance



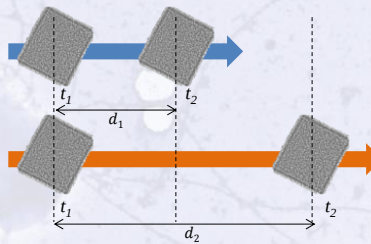
□ Constraint elements for obstacle avoidance using BPMs

5. Omnidirectional motion (holonomic motion)

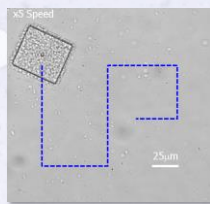
- Direction of electric field



- Displacement
- ➡ : Magnitude of electric field



- Motion example



Kim Group 2007

▪ Control characteristics

- ✓ The direction of electric field results from x voltage, y voltage inputs.
- ✓ The magnitude of electric field is proportional to the sum of x voltage, y voltage inputs.
- ✓ The superposed electric field can be a range of $0 \sim 360^\circ$.
- ✓ The maximum resultant control input is 20 V/cm in the system.

21

II Static Obstacle Avoidance



□ Proposed Static Obstacle Avoidance Approach

1. Obstacle avoidance approach based on an objective function

$$f(U_x, U_y) = \alpha \text{ heading}(U_x, U_y, \text{Goal}) + \gamma \text{ movement}(U_x, U_y) + \omega \text{ clearance}(U_x, U_y) + \delta \text{ control}(U_x, U_y)$$

- 1) $\text{heading}()$: to choose the input which makes BPM head to the goal
- 2) $\text{movement}()$: to choose the input which makes BPM move a longer displacement
- 3) $\text{clearance}()$: to avoid the input which makes BPM collide to obstacles
- 4) $\text{control}()$: to choose the input which makes BPM move toward strong controllable area

▪ The procedure to choose the control input from the objective function

1. Consider the instant position of a BPM with boundary information
2. Calculate each function of the objective function depending on all admissible control inputs
3. Find an optimal control input which has the maximum cost of the objective function

22

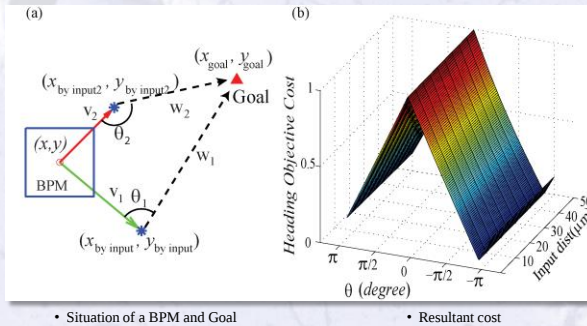
II Static Obstacle Avoidance



□ Proposed Static Obstacle Avoidance Approach

2. heading function

$$\text{heading}(U_x, U_y, \text{Goal}) = \frac{v \cdot w}{|v||w|} \div \pi$$



3. movement function

$$\text{movement}(U_x, U_y) = \beta_4 t_s \sqrt{U_x^2 + U_y^2}$$

23

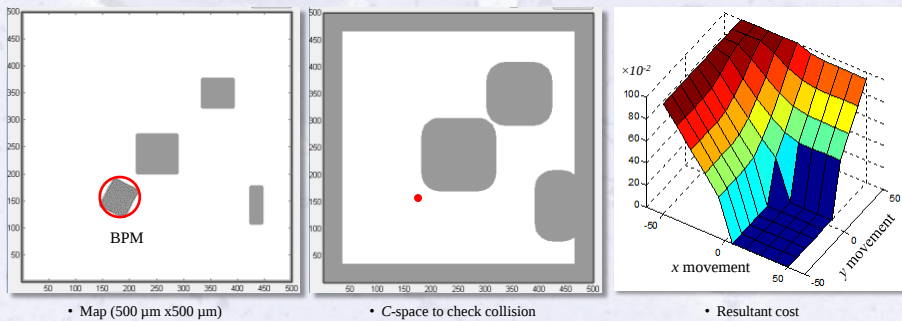
II Static Obstacle Avoidance



□ Proposed Static Obstacle Avoidance Approach

4. clearance function

$$\text{clearance}(U_x, U_y) \propto \frac{1}{\text{dist}(\text{cspace})}$$



24

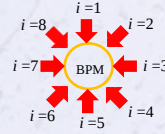
II Static Obstacle Avoidance



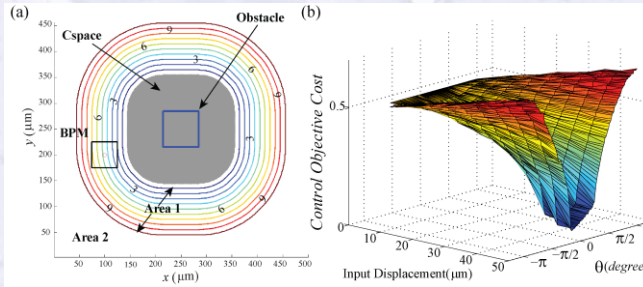
□ Proposed Static Obstacle Avoidance Approach

5. control function

$$\text{control}(U_x, U_y) = \sum_{i=1}^8 \frac{\vec{EF} \cdot \text{Input}(U_{xi}, U_{yi})}{|\vec{EF}|}$$



• At the next position



• Intrinsic potential field

• Resultant cost

25

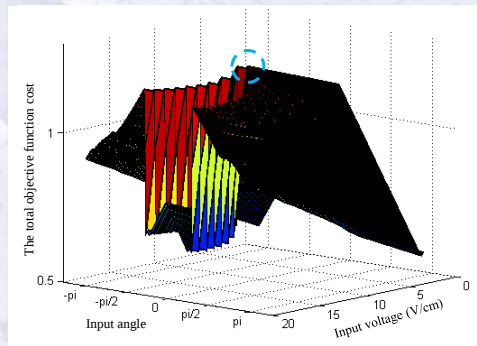
II Static Obstacle Avoidance



□ Proposed Static Obstacle Avoidance Approach

6. The chosen input from total value of the objective function

$$f(U_x, U_y) = \alpha \text{ heading}(U_x, U_y, \text{Goal}) + \gamma \text{ movement}(U_x, U_y) + \omega \text{ clearance}(U_x, U_y) + \delta \text{ control}(U_x, U_y)$$



• Result of the objective function

▪ Characteristic of the objective function

✓ Optimal input to maximize the cost of objective function depending on weight values of α , γ , ω , δ .

26

II Static Obstacle Avoidance



□ Experimental Results

1. System setup

- Obstacle structures
 - Material : SU-8 2010
 - Height : 20 μm
- BPMs
 - Material : SU-8 2002
 - Shape : $32 \times 30 \mu\text{m}^2$
 - Height : 3 μm
- Control System
 - 0.16 sampling time
 - C++ programming
 - GUI interface
- Experiment Chamber
 - Material : PDMS
 - Filled with PBS buffer
 - Two pairs of platinum wire



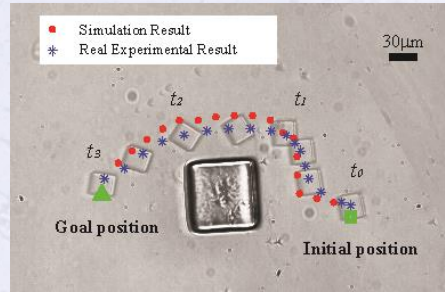
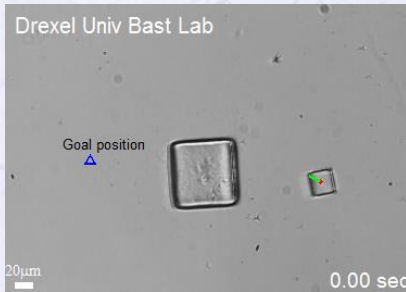
27

II Static Obstacle Avoidance



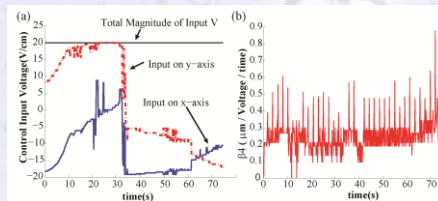
□ Experimental Results

2. Single obstacle avoidance with simulation result



- One obstacle environment ($71 \times 74 \mu\text{m}^2$)
- Maximum Voltage input: 20 V/cm
- Parameters for algorithm

α	γ	ω	δ	β_1	β_2	β_3	β_4
0.25	0.3	0.5	0.5	0.01	0.03	0.01	0.32



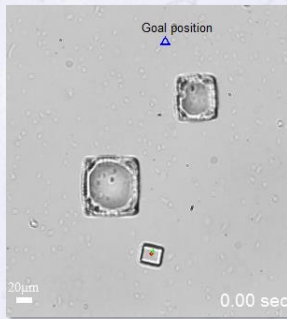
28

II Static Obstacle Avoidance



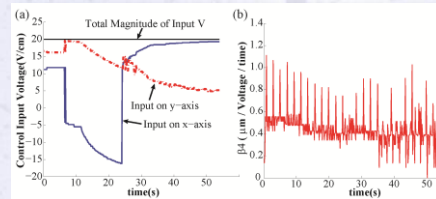
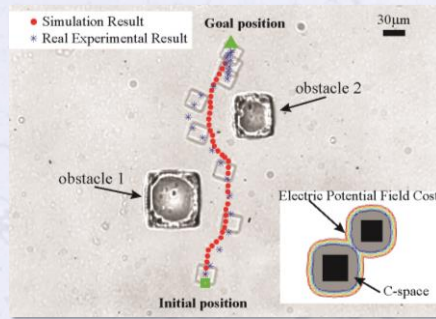
Experimental Results

3. Two obstacles avoidance with simulation result



- Two obstacles environment ($71 \times 74 \mu\text{m}^2$ and $52 \times 57 \mu\text{m}^2$)
- Maximum Voltage input: 20 V/cm
- Parameters for algorithm

α	γ	ω	δ	β_1	β_2	β_3	β_4
0.5	0.4	0.8	0.41	0.1	0.02	0.01	0.14



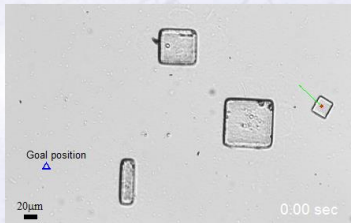
29

II Static Obstacle Avoidance

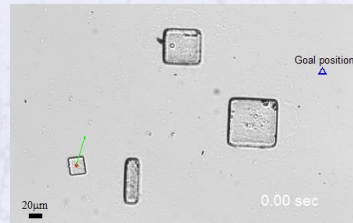


Experimental Results

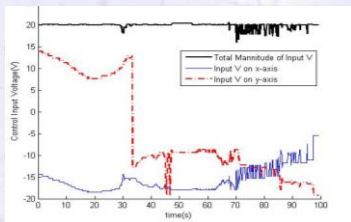
4. Routing motion with different weight values



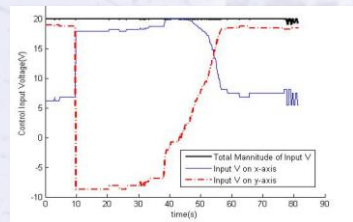
(heading : 0.4, movement : 0.3, clearance: 0.6, control : 0.55)



(heading : 0.45, movement: 0.3, clearance: 0.6, control : 0.7)



• Control input



• Control input

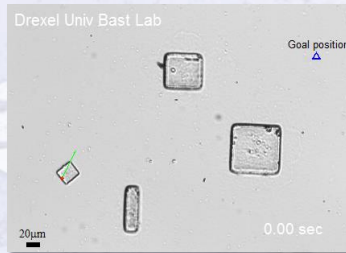
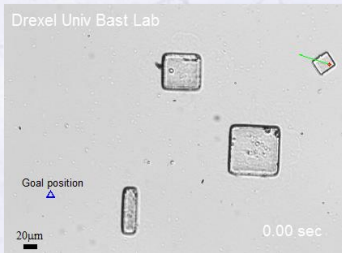
30

II Static Obstacle Avoidance

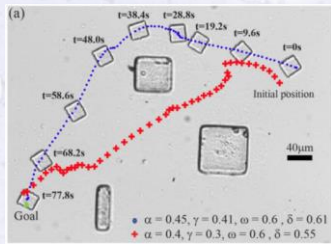


Experimental Results

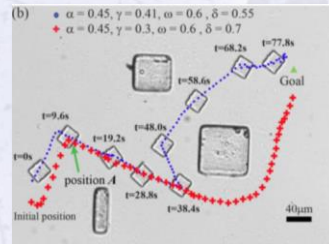
5. Routing motion with different weight values II



(heading : 0.45 movement : 0.41, clearance: 0.6, control : 0.61) (heading : 0.45, movement: 0.41, clearance: 0.6, control : 0.55)



• Comparison of trajectories



• Comparison of trajectories

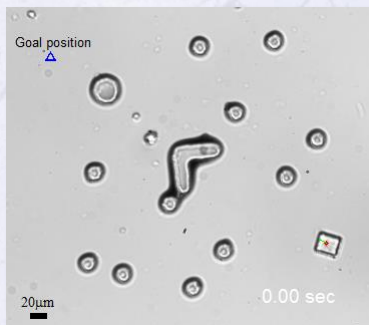
31

II Static Obstacle Avoidance

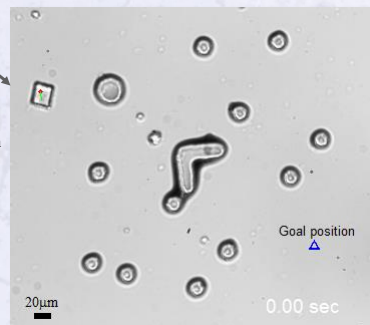


Experimental Results

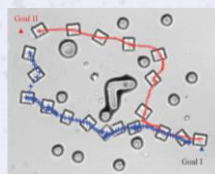
6. Routing motion in Multiple obstacles with different weight values



$\alpha = 0.8, \gamma = 0.5, \omega = 0.54, \delta = 0.5$



$\alpha = 0.8, \gamma = 0.5, \omega = 0.44, \delta = 0.5$



• Comparison of trajectories

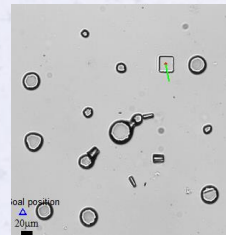
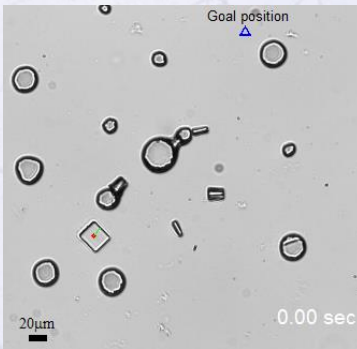
32

II Static Obstacle Avoidance



Experimental Results

7. Other Multiple obstacles avoidance results



	Min d between obstacles	Total Exp. No	Success rate
One obstacle	N/A	3	100%
Two obstacles	60	3	100%
Three obstacles	50	10	100%
Multiple obstacles	30	18	88%

Summary of experimental results

- ✓ The feasibility of the algorithm is verified with different conditions and various BPMs.
- ✓ The trajectories result from the different weighting $\alpha, \gamma, \omega, \delta$.
- ✓ Most cases have applied BPMs with the maximum control input voltage.

33

CONTENTS



I. Introduction

- Motivation
- Reviews
- Objective

II. Research works

- Hydrodynamics of Bacterial carpet using μ PIV
- Static Obstacle Avoidance for Bacteria Powered Microrobots
- Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

IV. Future Works

V. Achievements

34

III Dynamic Obstacle Avoidance

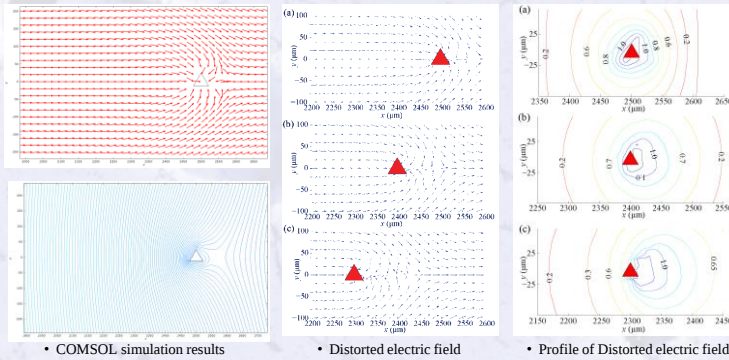


□ Constraint elements for obstacle avoidance using BPMs

1. Distorted electric field around dynamic obstacles : undesired control result

▪ Undesired control result

- COMSOL Multiphysics Simulation Setup : Moving mesh, 10 $\mu\text{m/s}$ with $-x$ -direction. Electric field with 10 V/cm



▪ Simulation Summary

- ✓ The distorted electric field area forms a ripple formation from the obstacle.
- ✓ The back side of the object has more ununiformed electric potential field.

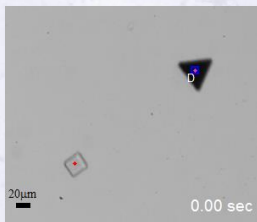
35

III Dynamic Obstacle Avoidance

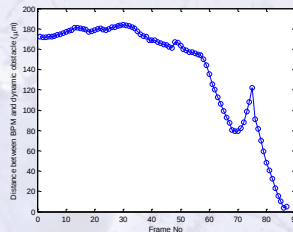


□ Constraint elements for obstacle avoidance using BPMs

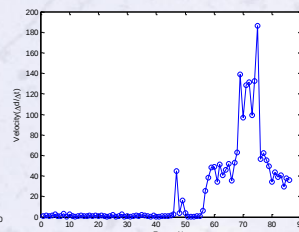
2. Unexpected motion speed of dynamic obstacle



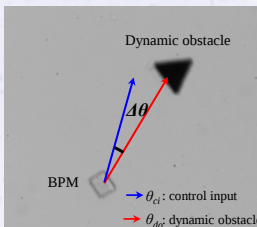
- Demonstrate of collision risk



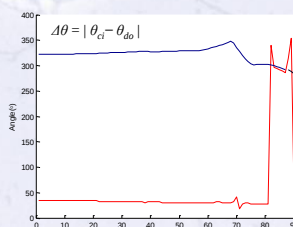
- Distance between BPM and dynamic obstacle



- Velocity of dynamic obstacle



- Description of $\Delta\theta$



- The difference of control input angle

▪ High probability of collision risk

- ✓ The high collision risk results from a sudden speed of dynamic obstacle.
- ✓ The motion of dynamic obstacle will be unpredictable.

36

III Dynamic Obstacle Avoidance



□ Proposed Dynamic Obstacle Avoidance Approach

1. Supplementary VFH method to the static obstacle avoidance approach

[Procedure to choose the optimal control input](#)

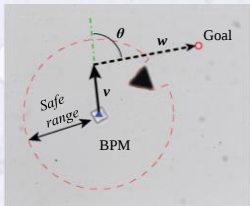
Step 1 : Exclude the control inputs which heads to obstacles using the redefined VFH ($v(U, \theta)$)

$$\theta_v = \{\theta_i\} \text{ for } BD(\theta_i) \leq \text{safe range}, 1 \leq i \leq 360$$

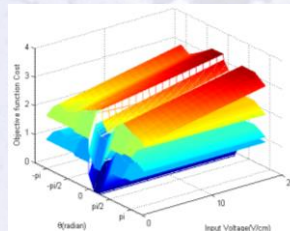
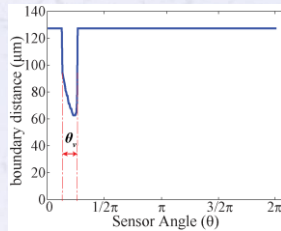
$$T_\theta = \min(|\theta - \theta_v|)$$

$$v(U, \theta) = \begin{cases} 0 & \text{if } T_\theta \leq \varepsilon_s \\ \frac{T_\theta^2}{T_{max}^2} & \text{if } \varepsilon_s < T_\theta \leq T_{max} \\ 1 & \text{if } T_{max} \leq T_\theta \end{cases}$$

Step 2 : Find the optimal control input using objective function on remained candidate inputs



■ Location of BPM and dynamic obstacle



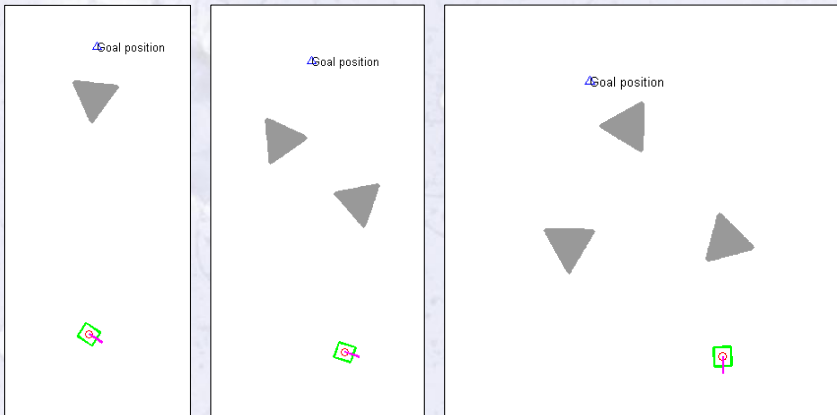
37

II Dynamic Obstacle Avoidance



□ Proposed Dynamic Obstacle Avoidance Approach

2. Simulation of the proposed approach using MATLAB



38

III Dynamic Obstacle Avoidance



□ Proposed Dynamic Obstacle Avoidance Approach

3. Evaluation of performance in terms of potential risk

Danger Index : $g_D(D_{BO}) \cdot g_A(A_{CO})$

➤ Product method based criterion

1st Factor : The relative distance factor between BPM and dynamic obstacle

D_{BO} : the distance between the BPM and the obstacle

$$g_D(D_{BO}) = \begin{cases} 0 & : D_{BO} \geq D_{max} \\ k \left(\frac{1}{D_{BO}} - \frac{1}{D_m} \right) & : D_{BO} < D_{max} \end{cases}$$

where, $k = \frac{D_{max}}{D_{min}}$

D_{max} = maximum allowable distance between the BPM and the obstacle (safe range)

$D_{min} = \text{Radius}_{BPM} * kv + \text{Movement}_{self}$, $kv = \frac{V_{mean \text{ of dynamic obstacle}}}{V_{mean \text{ of BPM}}}$

2nd Factor : The relative angle of control input comparing to the angle toward the dynamic obstacles

A_{CO} : the angle gap between the control input and the heading angel from BPM to the obstacle

$$g_A(A_{CO}) = \begin{cases} 0 & : A_{CO} \geq D_{blockAng}(D_{BO})/2 + \theta_{by \text{ self-actuation}} \\ \frac{A_{CO}}{D_{blockAng}(D_{BO})/2 + \theta_{by \text{ self-actuation}}} & : A_{CO} < D_{blockAng}(D_{BO})/2 + \theta_{by \text{ self-actuation}} \end{cases}$$

where, $D_{blockAng}(D_{BO})$ = the angle that represents occupied angle by obstacle depending on D_{BO}

39

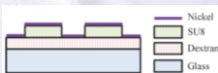
III Dynamic Obstacle Avoidance



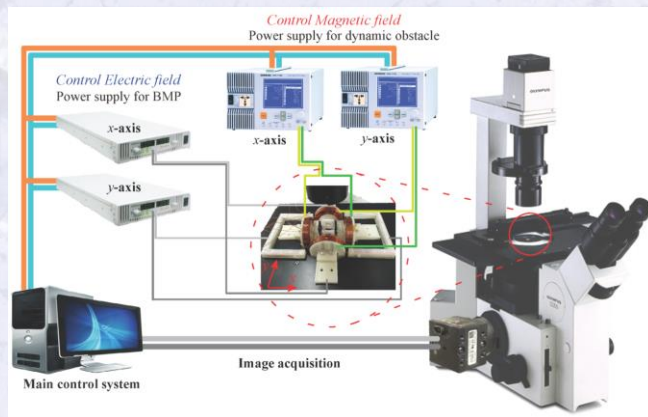
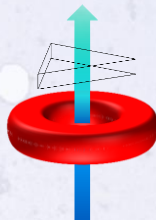
□ Experimental Results

1. System setup

- Dynamic obstacle structures
 - Material : SU-8 2010
 - Thickness : 3 μm
 - Nickel deposition : 200 nm



- z-coil to overcome friction
 - Lift force : 1.5mT (2V)
 - Tilt the structure



- Control System for main algorithm
 - 0.16 sampling time
 - C++ programming
 - GUI interface to input goal position
- Control System for dynamic obstacle
 - 0.16 sampling time
 - C++ programming
 - GUI interface for manual control

40

III Dynamic Obstacle Avoidance

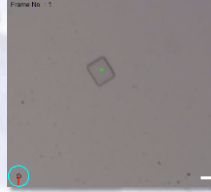
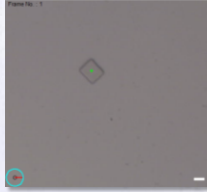


Experimental Results

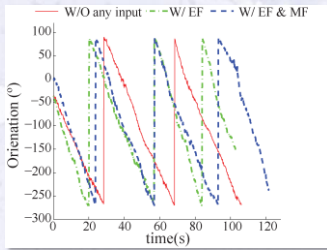
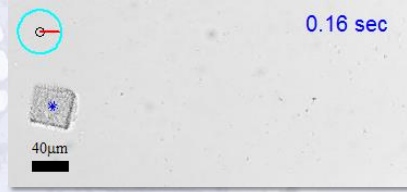
2. Magnetotaxis test on BPMs w/wo electric fields

- Setup : Magnetic field for more than 2 min with 20 Voltage input

1. Self-actuation test



2. Electric field test



- Comparison of orientation angle velocity

Magnetotaxis test results

- ✓ In terms of self-actuation, there is not critical difference with/without magnetic fields..
- ✓ The motion control of BPMs is not affected by the magnetic fields.
- ✓ It is not a problem with the application of magnetic fields for dynamic obstacles.

41

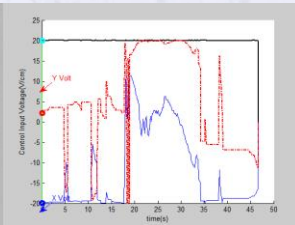
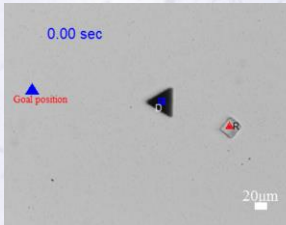
III Dynamic Obstacle Avoidance



Experimental Results

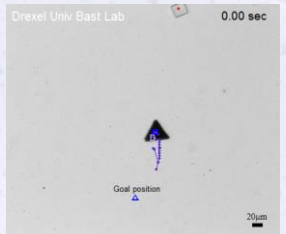
3. Single dynamic obstacle avoidance

Case I

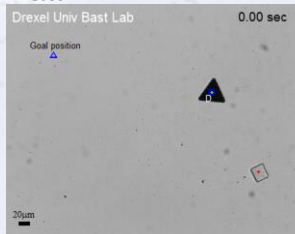


Case	α	γ	ω	δ	Safe range
I	0.5	0.6	0.5	0.7	100
II	0.5	0.5	0.7	0.5	80
III	0.3	0.2	0.5	0.7	100
IV	0.3	0.4	0.6	0.5	70

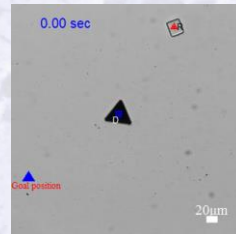
Case II



Case III



Case IV



42

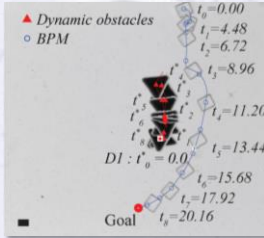
III Dynamic Obstacle Avoidance



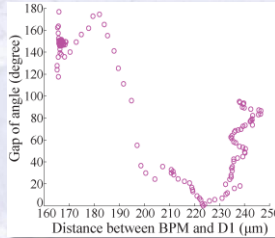
Experimental Results

4. Danger index for single dynamic obstacle avoidance experiments

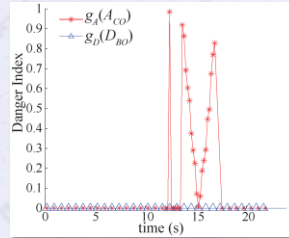
- Example using Case II



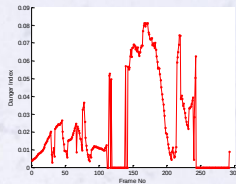
Resultant trajectories



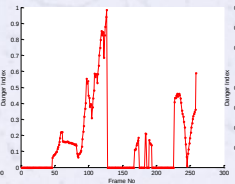
Relationship between gap and distance



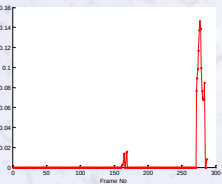
danger cost using $g_A(A_{co})$ and $g_D(D_{Bo})$



Danger index of Case I



Danger index of Case II



Danger index of Case IV

Case	BPM $\bar{v}$	Dynamic obstacle v		Mean distant
		mean	max	
I	9.6	12.0	92.6	40.2
II	18.7	5.3	102.4	30.3
III	15.8	29.1	57.4	29.1
IV	12.0	13.5	85.7	75.0

43

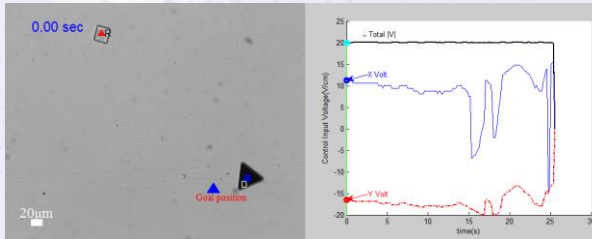
III Dynamic Obstacle Avoidance



Experimental Results

5. Single dynamic obstacle avoidance using strong self-actuation BPMs

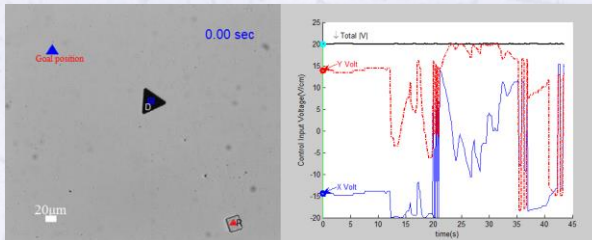
- Case V



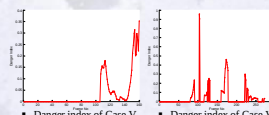
Case	α	γ	ω	δ	Safe range
V	0.3	0.2	0.5	0.6	100
VI	0.3	0.2	0.7	0.6	80

Case	β_1	β_2	β_3	β_4	Mean danger index
V	-20.3	12.1	6.8	0.8	0.095
VI	-7.6	-12.6	7.1	0.9	0.146

- Case VI



Case	BPM $\bar{v}$	Dynamic obstacle v		Mean distant
		mean	max	
V	20.1	9.7	99.1	40.2
VI	15.3	14.3	99.8	30.3



44

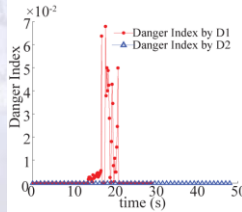
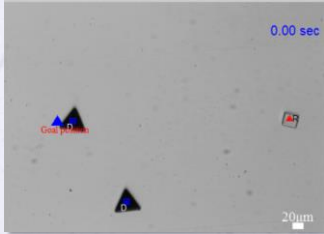
III Dynamic Obstacle Avoidance



Experimental Results

6. Multi dynamic obstacle avoidance

Case VII

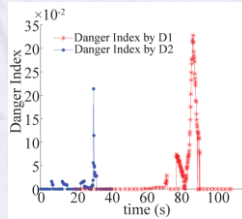
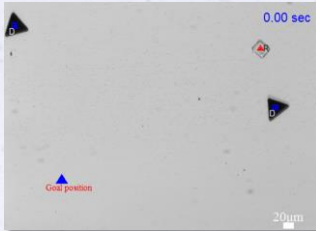


• Danger index of Case VII

Case	α	γ	ω	δ	Safe range
VII	0.3	0.4	0.6	0.5	120
VIII	0.3	0.2	0.7	0.5	100

Case	β_1	β_2	β_3	β_4	Mean danger index
VII	-1.89	5.03	0.01	0.76	0.15
VIII	5.01	6.20	0.08	0.81	0.02

Case VIII



• Danger index of Case VIII

Case	BPM $\bar{v}$	Dynamic obstacle v	
		mean	max
VII	10.9	12.7	116.1
VIII	15.3	14.3	100.9

Summary of experimental results

- ✓ The feasibility of the algorithm is verified with various situations.
- ✓ The performance is evaluated using the danger index.

45

CONTENTS



I. Introduction

- Motivation
- Reviews
- Objective

II. Research works

- Hydrodynamics of Bacterial carpet using μ PIV
- Static Obstacle Avoidance for Bacteria Powered Microrobots
- Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

IV. Future Works

V. Achievements

46

CONCLUSIONS



- ❑ Development of the obstacle avoidance algorithm for BPMs
 - Consideration of BPMs' characteristics and control systems design
 - Improvement of controllability for BPMs using electric fields
 - Robust approach for static and dynamic obstacle avoidance
- ❑ Validation through real experiments
 - Analysis of the motion of BPMs with the computed parameters
 - Comparison of performance with various environments
 - Evaluation of the potential risk using the danger index
- ❑ Quantification of the boundary effect
 - Visualization of the flow field on the bacterial carpet
 - Computation of the strength of the flow fields from tethered/untethered structures

47

CONTENTS



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- Reviews
- Objective

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- Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

IV. Future Works

V. Achievements

48



1. Adaptive parameters self-calibration for robust performance

- Probability approach - Machine learning, Neural network algorithm
- Increase of flexibility for environment

2. Swarming obstacle avoidance control

- Swarm control of multiple microrobots
- Centralized control
- Improvement of accuracy locomotion

CONTENTS



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- Reviews
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- Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

IV. Future Works

V. Achievements

Achievements



Journal Publication

7. H. Kim, U K. Cheang, and M.J. Kim "Autonomous motion control for dynamic obstacle avoidance using Bacteria Powered Microrobots ", (preparing)
6. J. Ali, H. Kim, U K. Cheang, and M. J. Kim, "MicroPIV measurements of flows induced by rotating microparticles near a boundary", Physics of Fluids, 2016 (pending)
5. U K. Cheang, H. Kim, M. Milutinovic, J. Choi, and M.J. Kim, "Feedback control of robotic achiral microswimmers," Journal of Bionic Engineering, 2016 (pending)
4. H. Kim, J. Ali, U K. Cheang, and M.J. Kim, "Micro manipulation using magnetic microrobots," Journal of Bionic Engineering, 2015, (pending)
3. H. Kim, U K. Cheang, D.H. Kim, and M.J. Kim, "Hydrodynamics of self-actuated bacteria carpet near boundary using microscale particle image velocimetry," Biomechanics, 2015, 9, p. 024121.
2. H. Kim, M.J. Kim, "Electric Field Control of Bacteria-Powered Microrobots (BPMs) Using Static Obstacle Avoidance Algorithm," IEEE Trans. Rob., DOI (identifier) 10.1109/TRO.2015.2504370 .
1. H. Kim, J. Ali, K. Phuyal, S. Park, M.J. Kim, "Investigation of bacterial chemotaxis using a simple three-point microfluidic system". BioChip Journal, 2015, 9(1), 50-58

Conference proceeding

5. H. Kim, U K. Cheang, and M.J. Kim, "Motion planning for particle based Microrobots for static obstacle avoidance", IEEE/RSJ IROS, 2016, Korea (pending)
4. J. Ali, H. Kim, Y. Liu, U K. Cheang, W. Sun, M.J. Kim, "Fabrication and magnetic control of alginate-based cellular microrobots," WBC, 2016.: Montreal, Canada.
3. U K. Cheang, H. Kim, D. Milutinovic, J. Choi, L. Rogowski, and M.J. Kim, "Feedback control of three-bead achiral microswimmers," URAI. 2015.: Goyang city, Korea. (Best Paper)
2. H. Kim, U K. Cheang, A.A. Julius, and M.J. Kim, "Dynamic obstacle avoidance for bacteria-powered microrobots," IEEE/RSJ IROS. 2015.: Hamburg, Germany.
1. H. Kim, U K. Cheang, and M.J. Kim, "Obstacle avoidance method for MicroBioRobots using electric field control," IEEE-CYBER. 2013.: Hong Kong, China (Final list for best paper)

51

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52



Q & A