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.
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)

Received Paper

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 magnetized Tetrahymena pyriformis cells by amagnetic field with Model Predictive Control, International Journal of Robotics Research, (01 2013): 129. doi:


TOTAL: 8
Number of Papers published in peer-reviewed journals:

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

Received | Paper
---------|---------

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):

Received | Paper
---------|---------

TOTAL:
<table>
<thead>
<tr>
<th>Received</th>
<th>Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>08/27/2013</td>
<td>5.00 Yan Ou, Paul Kim, Min Jun Kim, Anak Agung Julius, Aaron Becker. Feedback Control of Many Magnetized Tetrahymena pyriformis Cells by Exploiting Phase Inhomogeneity, IEEE/RSJ International Conference on Intelligent Robots and Systems. 03-NOV-13, . : ,</td>
</tr>
<tr>
<td>09/15/2014</td>
<td>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, . : ,</td>
</tr>
<tr>
<td>09/15/2014</td>
<td>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, . : ,</td>
</tr>
<tr>
<td>10/08/2015</td>
<td>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, . : ,</td>
</tr>
<tr>
<td>10/08/2015</td>
<td>20.00 Yan Ou, Peter Kang, Min Jun Kim, Anak Agung Julius. Algorithms for Simultaneous Motion Control of Multiple T. Pyriformis Cells: Model Predictive Control and Particle Swarm Optimization, IEEE International Conference of Robotics and Automation. 26-MAY-15, . : ,</td>
</tr>
<tr>
<td><strong>TOTAL:</strong></td>
<td><strong>7</strong></td>
</tr>
</tbody>
</table>
Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

<table>
<thead>
<tr>
<th>Received</th>
<th>Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>08/29/2012</td>
<td>2.00 MINJUN KIM, KIRAN PHUYAL. Mechanics of Swimming of Multi-body Bacterial Swarmers Using Non-Labeled Cell Tracking Algorithm, Physics of Fluids (05 2012)</td>
</tr>
<tr>
<td>09/15/2014</td>
<td>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)</td>
</tr>
<tr>
<td>09/15/2014</td>
<td>7.00 Dal Hyung Kim, Paul Seung Soo Kim, Kyoungwoo Lee, JinSeok Kim, Min Jun Kim. Galvanotactic behavior of Tetrahymenapryiformis under electric fields, Journal of Micromechanics &amp; Microengineering (08 2013)</td>
</tr>
</tbody>
</table>

TOTAL: 3

Number of Manuscripts:

Books

<table>
<thead>
<tr>
<th>Received</th>
<th>Book</th>
</tr>
</thead>
</table>

TOTAL: 1

Received       | Book Chapter

TOTAL:
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

<table>
<thead>
<tr>
<th>NAME</th>
<th>PERCENT_SUPPORTED</th>
<th>Discipline</th>
</tr>
</thead>
<tbody>
<tr>
<td>HOYEON KIM</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>KIRAN PHYJAL</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>ADAM G.W. BOWER</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>PAUL SEUNGSOO KIM</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>JAYAMARY DIVYA RAVICHADNI</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>U KEI CHEANG</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>FTE Equivalent:</td>
<td>4.25</td>
<td></td>
</tr>
<tr>
<td>Total Number:</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

Names of Post Doctorates

<table>
<thead>
<tr>
<th>NAME</th>
<th>PERCENT_SUPPORTED</th>
</tr>
</thead>
<tbody>
<tr>
<td>FARAH TENGRA</td>
<td>0.25</td>
</tr>
<tr>
<td>FTE Equivalent:</td>
<td>0.25</td>
</tr>
<tr>
<td>Total Number:</td>
<td>1</td>
</tr>
</tbody>
</table>

Names of Faculty Supported

<table>
<thead>
<tr>
<th>NAME</th>
<th>PERCENT_SUPPORTED</th>
<th>National Academy Member</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINJUN KIM</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>CYNTHIA COLLINS</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>ANAK AGUNG JULIUS</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>FTE Equivalent:</td>
<td>2.00</td>
<td></td>
</tr>
<tr>
<td>Total Number:</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>
### Names of Under Graduate students supported

<table>
<thead>
<tr>
<th>NAME</th>
<th>PERCENT_SUPPORTED</th>
<th>Discipline</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAMIEN TURCHI</td>
<td>0.25</td>
<td>Mechanical Eng.</td>
</tr>
<tr>
<td>LOUIS ROGOWSKI</td>
<td>0.45</td>
<td>Mechanical Eng.</td>
</tr>
<tr>
<td>ALEXANDRA DEAL</td>
<td>0.30</td>
<td>Biosciences</td>
</tr>
</tbody>
</table>

**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 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
- 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

### Names of Personnel receiving masters degrees

<table>
<thead>
<tr>
<th>NAME</th>
<th>Total Number:</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADAM G.W. BOWER</td>
<td>1</td>
</tr>
</tbody>
</table>

### Names of personnel receiving PHDs

<table>
<thead>
<tr>
<th>NAME</th>
<th>Total Number:</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAUL SEUNGSOO KIM</td>
<td>2</td>
</tr>
<tr>
<td>HOYEON KIM</td>
<td></td>
</tr>
</tbody>
</table>

### Names of other research staff

<table>
<thead>
<tr>
<th>NAME</th>
<th>PERCENT_SUPPORTED</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTE Equivalent:</td>
<td></td>
</tr>
<tr>
<td>Total Number:</td>
<td></td>
</tr>
</tbody>
</table>

### 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 1\textsuperscript{st}, 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 $\mu$PIV
  • Static Obstacle Avoidance for Bacteria Powered Microrobots
  • Dynamic Obstacle Avoidance for Bacteria Powered Microrobots
III. Conclusion
IV. Future Works
V. Achievements
I. Introduction
   • Motivation
   • Reviews
   • Objective

II. Research works
   • Hydrodynamics of Bacterial carpet using μPIV
   • Static Obstacle Avoidance for Bacteria Powered Microrobots
   • Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

IV. Future Works

V. Achievements
Motivation

- Technologic Issues for Microrobotics

- Fabrication
  - Artificial microswimming robot
  - Hybrid microswimming robot

- Control

Issues for the advanced task
- Localization
- Navigation
- Motion control for specific tasks

- Autonomous navigation
  - Support optimal path
  - Prevent damage of microrobot
  - Save time, energy
  - Increase efficiency

Reviews

- Autonomous motion control for navigation
  1. Micromanipulation
  - Microassembly test result using A*
  - Cell transportation using RRT
  - Motion planning using RRT
  - Micromanipulation
  - Micromanipulator 3
  - Micromanipulator 4

- Optical Tweezer
  - Test F 2011

- Magnetic field for Rolling microrobot
  - Test C 2015
Objectives

• An autonomous navigation algorithm using Bacteria Powered Microrobots
  1. Static obstacle avoidance
  2. Dynamic obstacle avoidance

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

CONTENTS

I. Introduction
   • Motivation
   • Reviews
   • Objective

II. Research works
   • Hydrodynamics of Bacterial carpet using μPIV
     • Static Obstacle Avoidance for Bacteria Powered Microrobots
     • Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

IV. Future Works

V. Achievements
Introduction of Bacteria Powered Microrobots (BPMs)

- Concept of BPM
  - Flagellum motor
  - Swimming motion of bacteria

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 µm/s
- Random walk

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

Fabrication of Bacteria Powered Microrobots

- Fabrication of microstructure
- Release microstructure by Dextran layer
- Swarming agar plate (Serratia marcescens)

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
I Hydrodynamics of Bacterial carpet

Propulsive force by bacterial carpet

1. System setup

- μPIV setup
  - Laser: 633 nm He-Ne laser
  - Fluorescent bead size: 0.2 μm diameter
  - Camera: High speed camera 250 fps
  - Objective lens: 100 x

- Tethered structure
  - Dimension: 32 x 34 μm²
  - Thickness: 35 μm using SU-8 2035

- Untethered structure (BPM)
  - Dimension: 32 x 34 μm²
  - Thickness: 3 μm using SU-8 2002

- Observed planes
  - Untethered case: 12 planes (0~22 μm)
  - Tethered case: 1 plane (1 μm)

2. Experimental results: Tethered structure cases

- Results summary
  - There is 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.
I Hydrodynamics of Bacterial carpet

Propulsive force by bacterial carpet

3. Experimental results: Untethered structure cases

- Untethered structure (Self-actuation of BPM)
- MSD comparison

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 μm².

I Hydrodynamics of Bacterial carpet

Propulsive force by bacterial carpet

4. Comparison of ensemble velocity

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
<th>std</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tethered</td>
<td>10.2 μm/s</td>
<td>5.3</td>
</tr>
<tr>
<td>Untethered</td>
<td>20 μm/s</td>
<td>10.4</td>
</tr>
</tbody>
</table>

Results summary

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

• Motivation
• Reviews
• Objective

II. Research works

• Hydrodynamics of Bacterial carpet using μPIV
• Static Obstacle Avoidance for Bacteria Powered Microrobots
• Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

IV. Future Works

V. Achievements

II Static Obstacle Avoidance

Constraint elements for obstacle avoidance using BPMs

1. Self-actuation of BPMs

• Uncontrollable motion

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

Self-actuation velocities

\[ V_x = \dot{p}_1 \beta_1, \quad V_y = \dot{p}_2 \beta_2, \quad \alpha = \dot{p}_3 \beta_3 \]

\[ \beta_1 = \frac{1}{k_r} \sum_{i=1}^{n} \cos \theta_i \quad \beta_2 = \frac{1}{k_r} \sum_{i=1}^{n} \sin \theta_i \]

\[ \beta_3 = \frac{1}{k_r} \sum_{i=1}^{n} (b_{ix} \sin \theta_i - b_{iy} \cos \theta_i) \]
Constraint elements for obstacle avoidance using BPMs

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, \( V_x = \beta \beta_1, \quad V_y = \beta \beta_2, \quad \alpha = \beta \beta_3 \), \( \beta_4 \): Electrophoretic property

   \( \beta \): mean propulsive force (0.41 pN).

   - Kinematic model of BMP’s locomotion
     \[ p_i = p_{i-1} + \text{Locomotion}_{self-actuation} + \text{Locomotion}_{electrokinetic} \]

2. Reliability of kinematic model
   - Modeling Validation using 40 × 43 μm²
   - Modeling Validation using 20 × 23 μm²
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. \( (9.1 \times 10^{-17} \text{ kg}, -1.6021 \times 10^{11} \text{ C}) \)
     - 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 weak.

II Static Obstacle Avoidance

Constraint elements for obstacle avoidance using BPMs

4. The effect of distorted electric field

Demonstration Result
- BPM cannot move at zero potential area.
- BPM follows the deformed electric field.
Constraint elements for obstacle avoidance using BPMs

5. Omnidirectional motion (holonomic motion)

- Direction of electric field
- Displacement
- Control characteristics
  - Direction of electric field results from $x$ voltage, $y$ voltage inputs.
  - Magnitude of electric field is proportional to the sum of $x$ voltage, $y$ voltage inputs.
  - The superposed electric field can be a range of $0$~$360^\circ$.
  - The maximum resultant control input is 20 V/cm in the system.

Proposed Static Obstacle Avoidance Approach

1. Obstacle avoidance approach based on an objective function

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

1) heading( ) : to choose the input which makes BPM head to the goal
2) movement( ) : to choose the input which makes BPM move a longer displacement
3) clearance( ) : to avoid the input which makes BPM collide to obstacles
4) 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
II Static Obstacle Avoidance

- Proposed Static Obstacle Avoidance Approach
  2. heading function
  \[
  \text{heading}(U_x, U_y, \text{Goal}) = \frac{\arctan(V_x, V_y)}{\pi} + \pi
  \]

  - Situation of a BPM and Goal
  - Resultant cost

  3. movement function
  \[
  \text{movement}(U_x, U_y) = \beta \cdot \sqrt{U_x^2 + U_y^2}
  \]

II Static Obstacle Avoidance

- Proposed Static Obstacle Avoidance Approach
  4. clearance function
  \[
  \text{clearance}(U_x, U_y) \propto \frac{1}{\text{dist(cspace)}}
  \]

  - Map (500 μm x 500 μm)
  - C-space to check collision
  - Resultant cost
II Static Obstacle Avoidance

Proposed Static Obstacle Avoidance Approach

5. control function

\[ \text{control}(U_x, U_y) = \sum_{i=1}^{8} \left( \frac{\text{EF} \cdot \text{Input}(U_{x,i}, U_{y,i})}{|\text{EF}|} \right) \]

- Intrinsic potential field
- Resultant cost

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 \( \alpha, \gamma, \omega, \delta \).
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 × 30 µm²
  - 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

II Static Obstacle Avoidance

2. Single obstacle avoidance with simulation result

- One obstacle environment (71 × 74 µm²)
- Maximum Voltage input: 20 V/cm
- Parameters for algorithm
  
  \[
  \begin{array}{cccccccc}
    \alpha & \gamma & \omega & \delta & \beta_0 & \beta_1 & \beta_2 & \beta_3 \\
    0.25 & 0.3 & 0.5 & 0.5 & 0.01 & 0.03 & 0.01 & 0.32
  \end{array}
  \]
II Static Obstacle Avoidance

- Experimental Results

3. Two obstacles avoidance with simulation result

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

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$\gamma$</th>
<th>$\omega$</th>
<th>$\delta$</th>
<th>$\beta_1$</th>
<th>$\beta_2$</th>
<th>$\beta_3$</th>
<th>$\beta_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.4</td>
<td>0.8</td>
<td>0.41</td>
<td>0.1</td>
<td>0.02</td>
<td>0.01</td>
<td>0.14</td>
</tr>
</tbody>
</table>

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
II Static Obstacle Avoidance

Experimental Results

5. Routing motion with different weight values II

- Comparison of trajectories

6. Routing motion in Multiple obstacles with different weight values

- Comparison of trajectories
II Static Obstacle Avoidance

7. Other Multiple obstacles avoidance results

<table>
<thead>
<tr>
<th>Obstacle</th>
<th>Min d between obstacles</th>
<th>Total Exp. No</th>
<th>Success rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>One obstacle</td>
<td>N/A</td>
<td>3</td>
<td>100%</td>
</tr>
<tr>
<td>Two obstacles</td>
<td>60</td>
<td>3</td>
<td>100%</td>
</tr>
<tr>
<td>Three obstacles</td>
<td>50</td>
<td>10</td>
<td>100%</td>
</tr>
<tr>
<td>Multiple obstacles</td>
<td>30</td>
<td>18</td>
<td>88%</td>
</tr>
</tbody>
</table>

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.

CONTENTS

I. Introduction
   • Motivation
   • Reviews
   • Objective

II. Research works
   • Hydrodynamics of Bacterial carpet using $\mu$PIV
   • Static Obstacle Avoidance for Bacteria Powered Microrobots
   • Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

IV. Future Works

V. Achievements
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 simulation results
     - Distorted electric field
     - Profile of Distorted electric field

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

2. Unexpected motion speed of dynamic obstacle
   - 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.
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 \( (v(U, \theta)) \)

\[
\theta_i = \theta_i \quad \text{for} \quad BD(\theta_i) \leq \text{safety range}, \quad 1 \leq i \leq 360
\]

\[
T_\theta = \min(\theta - \theta_i)
\]

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

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

II Dynamic Obstacle Avoidance

Proposed Dynamic Obstacle Avoidance Approach

2. Simulation of the proposed approach using MATLAB
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

\[
D_{BO} = \begin{cases} 
0 & : D_{BO} \geq D_{max} \\
\frac{k}{D_{BO}} & : D_{BO} < D_{max}
\end{cases}
\]

where, \( k = \frac{D_{max}}{D_{min}} \)

- \( D_{max} = \) maximum allowable distance between the BPM and the obstacle (safe range)
- \( D_{min} = \) Radius_{BPM} + Movement_{self} + \( \frac{\text{Vmean of distance change}}{\text{Vmean of BPM}} \)

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

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

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

Experimental Results

1. System setup

- Dynamic obstacle structures
  - Material: SU-8 2010
  - Thickness: 3 \( \mu \)m
  - 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
Experimental Results

2. Magnetotaxis test on BPMs w/o electric fields

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

1. Self-actuation test
2. Electric field test

- 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.

III Dynamic Obstacle Avoidance

3. Single dynamic obstacle avoidance

- Case I
- Case II
- Case III
- Case IV

<table>
<thead>
<tr>
<th>Case</th>
<th>α</th>
<th>β</th>
<th>γ</th>
<th>δ</th>
<th>Safe range</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.5</td>
<td>0.6</td>
<td>0.5</td>
<td>0.7</td>
<td>100</td>
</tr>
<tr>
<td>II</td>
<td>0.5</td>
<td>0.5</td>
<td>0.7</td>
<td>0.5</td>
<td>80</td>
</tr>
<tr>
<td>III</td>
<td>0.3</td>
<td>0.2</td>
<td>0.5</td>
<td>0.7</td>
<td>100</td>
</tr>
<tr>
<td>IV</td>
<td>0.3</td>
<td>0.4</td>
<td>0.6</td>
<td>0.5</td>
<td>70</td>
</tr>
</tbody>
</table>
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 $g(A_{\text{co}})$ and $g(D_{BO})$

<table>
<thead>
<tr>
<th>Case</th>
<th>BPM</th>
<th>Danger index</th>
<th>Mean</th>
<th>Max</th>
<th>Above</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>9.6</td>
<td>12.0</td>
<td>92.6</td>
<td>40.2</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>18.4</td>
<td>5.3</td>
<td>102.4</td>
<td>30.3</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>15.8</td>
<td>29.1</td>
<td>57.4</td>
<td>29.1</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>12.0</td>
<td>13.5</td>
<td>88.7</td>
<td>75.0</td>
<td></td>
</tr>
</tbody>
</table>

- Danger index of Case I
- Danger index of Case II
- Danger index of Case III
- Danger index of Case IV

7. Single dynamic obstacle avoidance using strong self-actuation BPMs
   - Case V
     - Danger index
     - Case VI
     - Danger index

<table>
<thead>
<tr>
<th>Case</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\gamma$</th>
<th>$\delta$</th>
<th>Above</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>0.3</td>
<td>0.2</td>
<td>0.5</td>
<td>0.6</td>
<td>100</td>
</tr>
<tr>
<td>VI</td>
<td>0.3</td>
<td>0.2</td>
<td>0.7</td>
<td>0.6</td>
<td>80</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case</th>
<th>$\alpha'$</th>
<th>$\beta'$</th>
<th>$\gamma'$</th>
<th>$\delta'$</th>
<th>Danger index</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>-20.3</td>
<td>12.1</td>
<td>6.8</td>
<td>0.8</td>
<td>0.095</td>
</tr>
<tr>
<td>VI</td>
<td>-7.6</td>
<td>-12.6</td>
<td>7.1</td>
<td>0.9</td>
<td>0.146</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case</th>
<th>BPM</th>
<th>Danger index</th>
<th>Mean</th>
<th>Max</th>
<th>Above</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>20.1</td>
<td>9.7</td>
<td>99.1</td>
<td>40.2</td>
<td></td>
</tr>
<tr>
<td>VI</td>
<td>15.3</td>
<td>14.3</td>
<td>99.8</td>
<td>30.3</td>
<td></td>
</tr>
</tbody>
</table>
Experimental Results

6. Multi dynamic obstacle avoidance

- Case VII

<table>
<thead>
<tr>
<th>Case</th>
<th>$\gamma$</th>
<th>$\delta$</th>
<th>$\omega$</th>
<th>Mean danger index</th>
</tr>
</thead>
<tbody>
<tr>
<td>VII</td>
<td>0.3</td>
<td>0.4</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>VIII</td>
<td>0.3</td>
<td>0.2</td>
<td>0.7</td>
<td>0.5</td>
</tr>
</tbody>
</table>

- Case VIII

<table>
<thead>
<tr>
<th>Case</th>
<th>$\beta_1$</th>
<th>$\beta_2$</th>
<th>$\beta_3$</th>
<th>$\beta_4$</th>
<th>Mean danger index</th>
</tr>
</thead>
<tbody>
<tr>
<td>VII</td>
<td>-1.89</td>
<td>5.03</td>
<td>0.01</td>
<td>0.76</td>
<td>0.15</td>
</tr>
<tr>
<td>VIII</td>
<td>5.01</td>
<td>6.20</td>
<td>0.08</td>
<td>0.81</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Danger index of Case VII

Danger index of Case VIII

Summary of experimental results

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

CONTENTS

I. Introduction
   - Motivation
   - Reviews
   - Objective

II. Research works
   - Hydrodynamics of Bacterial carpet using µPIV
   - Static Obstacle Avoidance for Bacteria Powered Microrobots
   - Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

IV. Future Works

V. Achievements
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

CONTENTS

I. Introduction
   - Motivation
   - Reviews
   - Objective

II. Research works
   - Hydrodynamics of Bacterial carpet using μPIV
   - Static Obstacle Avoidance for Bacteria Powered Microrobots
   - Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion

IV. Future Works

V. Achievements
Future works

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

I. Introduction
   • Motivation
   • Reviews
   • Objective

II. Research works
   • Hydrodynamics of Bacterial carpet using μPIV
   • Static Obstacle Avoidance for Bacteria Powered Microrobots
   • Dynamic Obstacle Avoidance for Bacteria Powered Microrobots

III. Conclusion
IV. Future Works
V. Achievements
Achievements

- Journal Publication

- Conference proceeding
  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)

Acknowledgements

I sincerely thank

- The committee members
  - Prof. Ajmal Yousuff
  - Prof. Young Cho
  - Prof. Boe-Chun Chang
  - Prof. Allen Guez
  - Prof. Min Jun Kim

- Current and past labmates
  - Dr. U Kei Cheang, Janiel Ali, Armin Darvish, Dr. Paul Kim, Dr. Gaurav Goyal, Dharma T. Varapula, Rafael Mulero, Dr. Anmiv Prabhu, Dr. Kevin Freedman, Dr. Dalhyung Kim, Dr. Wonjin Jo.

- Our collaborators
  - Dr. Agung Julius

- Colleagues
  - Dr. Qadus, Yoontae Kim, Dr. Jessica Snyder, Dr. Reyhan Taspinar, Chengyang Wang, Bin Lei, Yigong Liu, Luffi Agartan, Dong-Ook Kim and Hyunjoo Oh.

- All of the attendees
Q & A