

# Shaping a Swarm Using Wall Friction and a Shared Control Input

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**Abstract**—Micro- and nano-robots can be manufactured in large numbers. Large numbers of micro robots are required in order to deliver sufficient payloads, but the small size of these robots makes it difficult to perform onboard computation. Instead, these robots are often controlled by a global, broadcast signal. In our previous work we focused on a block-pushing task, where a swarm of robots pushed a larger block through a 2D maze. One surprising result was that humans that only knew the swarm’s mean and covariance completed the task faster than humans who knew the position of every robot [?]. Inspired by that work, we proved that we can control the mean position of a swarm and that with an obstacle we can control the swarm’s position variance ( $\sigma_x$  and  $\sigma_y$ ). We then wrote automatic controllers which could complete a block pushing task, but these controllers had some limitations [?]. One of the limitations was that we could only compress our swarm along the world  $x$  and  $y$  axes, and could not navigate workspaces with narrow corridors with other orientations. One solution to these problems would be a controller that regulates the swarm’s position covariance,  $\sigma_{xy}$ . For controlling  $\sigma_{xy}$ , we prove that the swarm position covariance  $\sigma_{xy}$  is controllable given boundaries with non-zero friction. We then prove that two orthogonal boundaries with high friction are sufficient to arbitrarily position a swarm of robots. We conclude by designing controllers that efficiently regulate  $\sigma_{xy}$ .

## I. INTRODUCTION

## II. THEORY

### III. POSITION CONTROL OF $n$ ROBOTS USING WALL FRICTION

Algorithm 4 can be extended to control the position of  $n$  robots using wall friction under several constraints. Assume an open workspace with four axis-aligned walls with infinite friction. The axis-aligned rectangle of dimension  $(w_f, h_f)$  containing the final configuration of  $n$  robots must be disjoint from the axis-aligned rectangle of dimension  $(w_s, h_s)$  containing the starting configuration of  $n$  robots. Without loss of generality, assume the final configuration is above the starting configuration. Furthermore, there must be at least  $\epsilon$  space above the final configuration,  $\epsilon$  below the starting configuration, and  $\epsilon + w_r$  to the left of the final and start configurations, where  $w_r$  is the width of a robot. The workspace is at least  $(\epsilon + w_r + \max(w_f, w_s), 2\epsilon + h_s, h_f)$ .

Let  $(0, 0)$  be the lower left corner of the workspace,  $p_k$  the  $x, y$  position of the  $k$ th robot, and  $f_k$  the final  $x, y$  position of the  $k$ th robot.

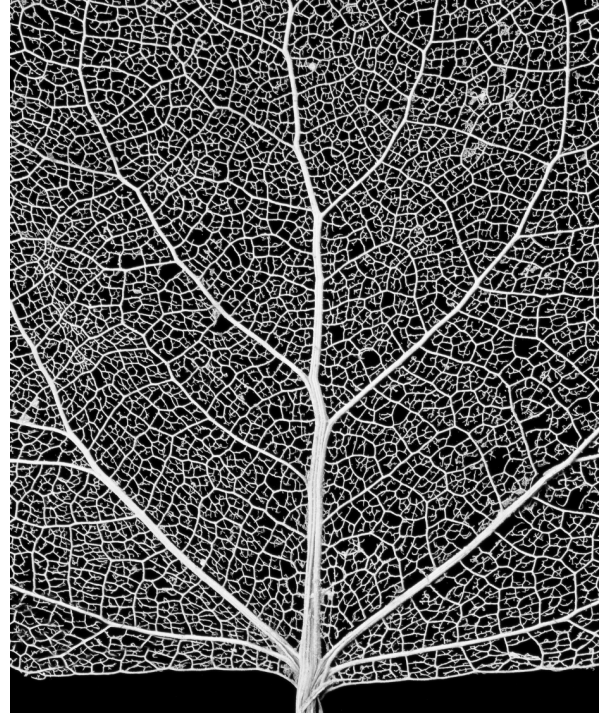


Fig. 1. Several real vascular networks exist in real world, which navigating a swarm with a global input would be a challenge because of the branches in the way.

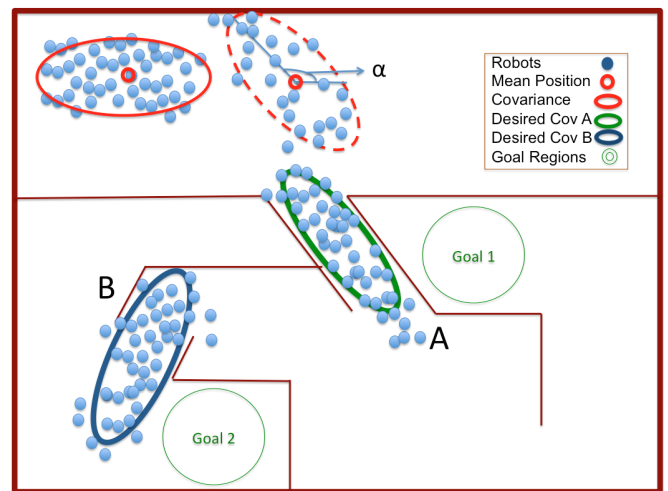


Fig. 2. We can control covariance of the swarm by using friction.

Fig. 3. Illustration of algorithm for position control of  $n$  robots using wall friction.

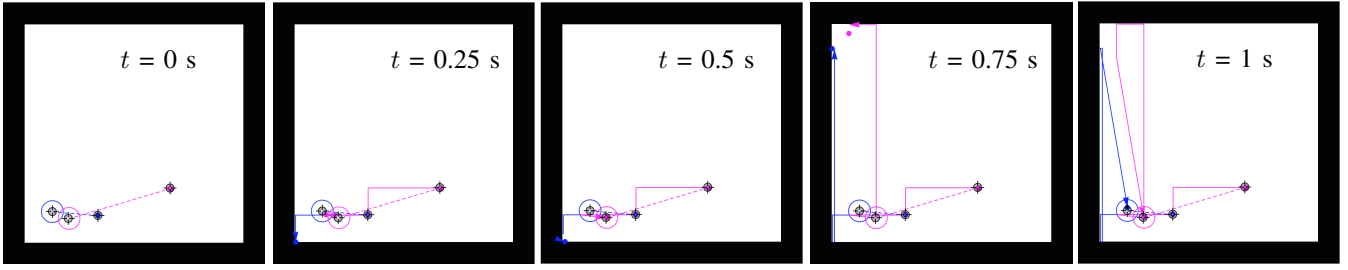


Fig. 4. Two robot positioning with using infinite friction for walls.

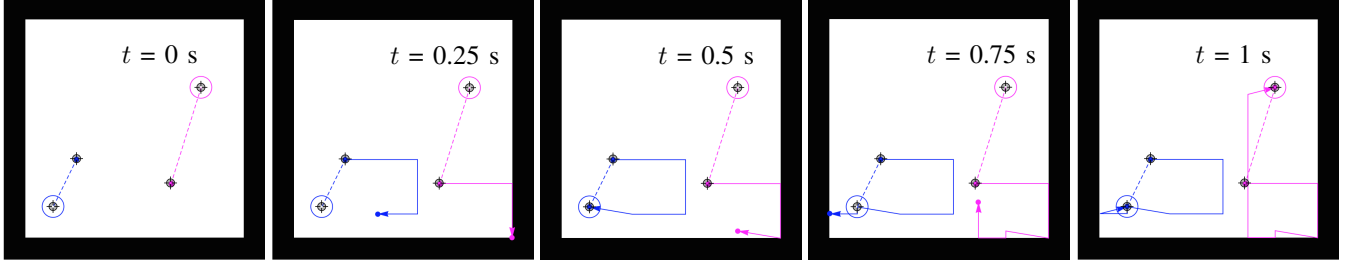


Fig. 5. Two robot positioning with using infinite friction for walls.

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**Algorithm 1** GenerateDesired $x$ -spacing( $s_1, s_2, e_1, e_2, L$ )

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**Require:** Knowledge of starting ( $s_1, s_2$ ) and ending ( $e_1, e_2$ ) positions of two robots. (0,0) is bottom corner,  $s_1$  is topmost robot,  $L$  is length of the walls. Current position of the robots are ( $r_1, r_2$ ).

**Ensure:**  $r_{1y} - r_{2y} \equiv s_{1y} - s_{2y}$

- 1:  $\Delta s_x \leftarrow s_{1x} - s_{2x}$
- 2:  $\Delta e_x \leftarrow e_{1x} - e_{2x}$
- 3:  $r_1 \leftarrow s_1, r_2 \leftarrow s_2$
- 4: **if**  $\Delta e_x < 0$  **then**
- 5:    $m \leftarrow (L - \max(r_{1x}, r_{2x}), 0)$     $\triangleright$  Move to right wall
- 6: **else**
- 7:    $m \leftarrow (-\min(r_{1x}, r_{2x}), 0)$     $\triangleright$  Move to left wall
- 8: **end if**
- 9:  $m \leftarrow m + (0, -\min(r_{1y}, r_{2y}))$     $\triangleright$  Move to bottom
- 10:  $r_1 \leftarrow r_1 + m, r_2 \leftarrow r_2 + m$     $\triangleright$  Apply move
- 11: **if**  $\Delta e_x - (r_{1x} - r_{2x}) > 0$  **then**
- 12:    $m \leftarrow (\min(\|\Delta e_x - \Delta s_x\|, L - r_{1x}), 0)$     $\triangleright$  Move right
- 13: **else**
- 14:    $m \leftarrow (-\min(\|\Delta e_x - \Delta s_x\|, r_{1x}), 0)$     $\triangleright$  Move left
- 15: **end if**
- 16:  $m \leftarrow m + (0, \epsilon)$     $\triangleright$  Move up
- 17:  $r_1 \leftarrow r_1 + m, r_2 \leftarrow r_2 + m$     $\triangleright$  Apply move
- 18:  $\Delta r_x = r_{1x} - r_{2x}$
- 19: **if**  $\Delta r_x \equiv \Delta e_x$  **then**
- 20:    $m \leftarrow (e_{1x} - r_{1x}, e_{1y} - r_{1y})$
- 21:    $r_1 \leftarrow r_1 + m, r_2 \leftarrow r_2 + m$     $\triangleright$  Apply move
- 22:   **return** ( $r_1, r_2$ )
- 23: **else**
- 24:   **return** GenerateDesired $x$ -spacing( $r_1, r_2, e_1, e_2, L$ )
- 25: **end if**

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**Algorithm 2** GenerateDesired $y$ -spacing( $s_1, s_2, e_1, e_2, L$ )

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**Require:** Knowledge of starting ( $s_1, s_2$ ) and ending ( $e_1, e_2$ ) positions of two robots. (0,0) is bottom corner,  $s_1$  is rightmost robot,  $L$  is length of the walls. Current position of the robots are ( $r_1, r_2$ ).

**Ensure:**  $r_{1x} - r_{2x} \equiv s_{1x} - s_{2x}$

- 1:  $\Delta s_y \leftarrow s_{1y} - s_{2y}$
- 2:  $\Delta e_y \leftarrow e_{1y} - e_{2y}$
- 3:  $r_1 \leftarrow s_1, r_2 \leftarrow s_2$
- 4: **if**  $\Delta e_y < 0$  **then**
- 5:    $m \leftarrow (L - \max(r_{1y}, r_{2y}), 0)$     $\triangleright$  Move to top wall
- 6: **else**
- 7:    $m \leftarrow (-\min(r_{1y}, r_{2y}), 0)$     $\triangleright$  Move to bottom wall
- 8: **end if**
- 9:  $m \leftarrow m + (0, -\min(r_{1x}, r_{2x}))$     $\triangleright$  Move to left
- 10:  $r_1 \leftarrow r_1 + m, r_2 \leftarrow r_2 + m$     $\triangleright$  Apply move
- 11: **if**  $\Delta e_y - (r_{1y} - r_{2y}) > 0$  **then**
- 12:    $m \leftarrow (\min(\|\Delta e_y - \Delta s_y\|, L - r_{1y}), 0)$     $\triangleright$  Move top
- 13: **else**
- 14:    $m \leftarrow (-\min(\|\Delta e_y - \Delta s_y\|, r_{1y}), 0)$     $\triangleright$  Move bottom
- 15: **end if**
- 16:  $m \leftarrow m + (0, \epsilon)$     $\triangleright$  Move right
- 17:  $r_1 \leftarrow r_1 + m, r_2 \leftarrow r_2 + m$     $\triangleright$  Apply move
- 18:  $\Delta r_y = r_{1y} - r_{2y}$
- 19: **if**  $\Delta r_y \equiv \Delta e_y$  **then**
- 20:    $m \leftarrow (e_{1x} - r_{1x}, e_{1y} - r_{1y})$
- 21:    $r_1 \leftarrow r_1 + m, r_2 \leftarrow r_2 + m$     $\triangleright$  Apply move
- 22:   **return** ( $r_1, r_2$ )
- 23: **else**
- 24:   **return** GenerateDesired $y$ -spacing( $r_1, r_2, e_1, e_2, L$ )
- 25: **end if**

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**Algorithm 3** WallFrictionArrange2Robots( $s_1, s_2, e_1, e_2, L$ )

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**Require:** Knowledge of starting ( $s_1, s_2$ ) and ending ( $e_1, e_2$ ) positions of two robots.  $(0,0)$  is bottom corner,  $s_1$  is rightmost robot,  $L$  is length of the walls.

```
1:  $\Delta s_x \leftarrow s_{1x} - s_{2x}$ 
2:  $\Delta s_y \leftarrow s_{1y} - s_{2y}$ 
3:  $\Delta e_x \leftarrow e_{1x} - e_{2x}$ 
4:  $\Delta e_y \leftarrow e_{1y} - e_{2y}$ 
5: if  $\Delta s_x < \Delta s_y$  then
6:   GenerateDesired $x$ -spacing( $s_1, s_2, e_1, e_2, L$ )
7:   GenerateDesired $y$ -spacing( $s_1, s_2, e_1, e_2, L$ )
8: else
9:   GenerateDesired $y$ -spacing( $s_1, s_2, e_1, e_2, L$ )
10:  GenerateDesired $x$ -spacing( $s_1, s_2, e_1, e_2, L$ )
11: end if
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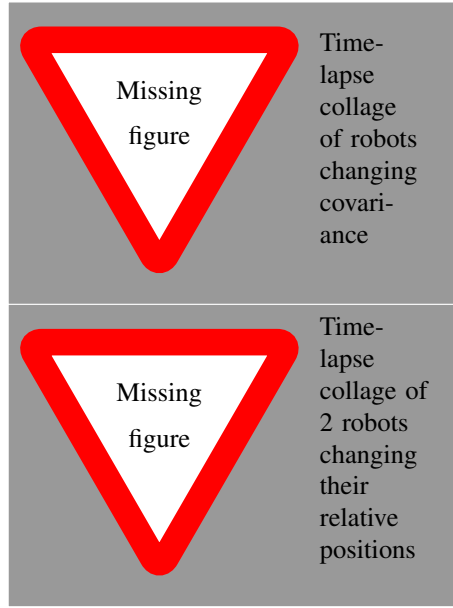
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**Algorithm 4** PositionControl $n$ RobotsUsingWallFriction( $k$ )

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1: move(  $-\epsilon, -r_{k,y}$  )
2: drift move left until  $r_k \equiv (0,0)$ 
3: drift move up until  $r_{ky} \equiv f_{ky}$ 
    $f_{kx} - f_{(k-1)x} \quad p_{kx} - p_{(k-1)x}$ 
4: move ( ,0)
```

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#### IV. SIMULATION

