Multi-Robot Perimeter Patrol in Adversarial Settings

Noa Agmon, Sarit Kraus and Gal A. Kaminka
Department of Computer Science
Bar Ilan University, Israel
{segaln, sarit, galk}@cs.biu.ac.il

Presenter: Solomon Ayalew

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Introduction

- Multi robot patrol in a closed area with the existence of an adversary

- Traditional approach is Visit the *area frequently*

- *If robots move in a deterministic way: Penetration is easy*

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Introduction cont.

- This paper:- Non deterministic Algorithm for a team of Homogenous patrol robots
  - Divide the perimeter in to segments ***i***
  - robot monitors 1 segment ***i*** per unit time cycle
  - robot @ segment ***i*** have 3 choices
    - Go to segment ***i-1*** or ***i+1*** or stay there ***(i)***

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Movement models

- 3 movement models
  1. DZCP : Directional Zero Cost Patrol
  2. BMP : Bidirectional Movement Patrol
  3. DCP : Directional Costly-Turn Patrol

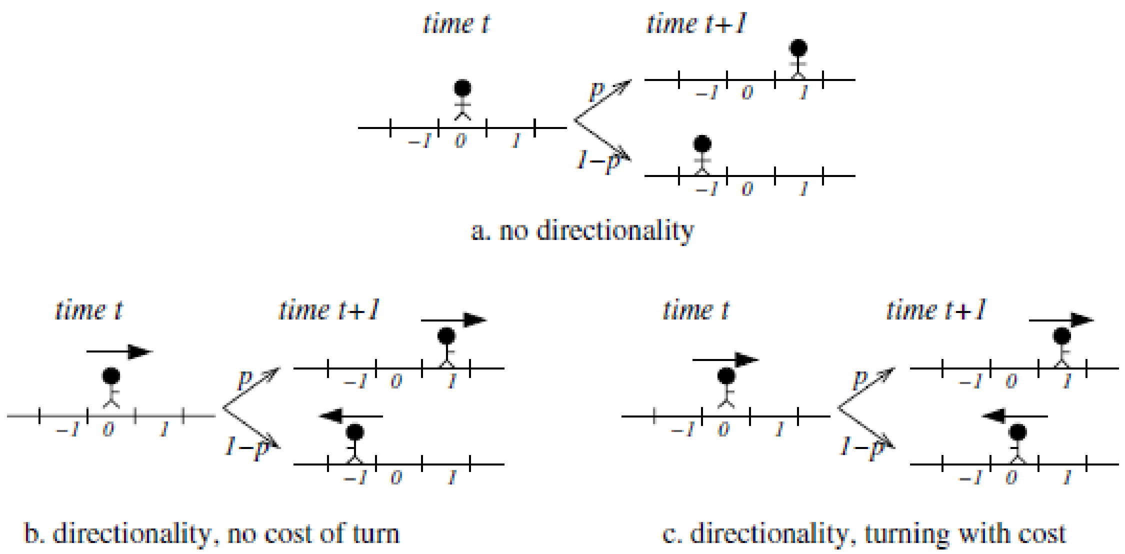

Fig. 2. Illustration of p's characterization of the three models of movement.

Adversarial model

- Adversarial model
  - The adversary is strong (has full knowledge of the system)
  - Know the patrol scheme

    1. # of robots, distance between them, their current position
    2. Movement model of robots & characterization of their movement
  - Can be learned by
    - observing for sufficiently long time
    - Assume worst case scenario

Goal

- Robots are responsible for detection not handling
  - Multiple penetration is the some as single penetration

- Adversary tries to penetrate @ the weakest spot in the cycle

- **Main goal:**
- Find a patrol algorithm that maximizes penetration detection in the weakest spot

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Algorithm

- Algorithm is characterized by a probability ***p***
  - ***p*** could be 1 => deterministic
  - So *0* <= ***p* <= *1***

Border Penetration Detection (BPD) problem

- Given
  - Circular fence of length ***l*** divided in to ***N*** segments
  - ***K*** robots uniformly distributed with ***d*** distance
    - ***d = N/k***
- Assume : it takes ***t*** time units for the adversary to penetrate

cont.

- let $f_i(p) = ppd_i$, $1 \leq i \leq d - 1$
- $\boldsymbol{ppd_i}$: probability of penetration detection
  - Probability that a segment will be visited at least ones during t time units

Cont.

- find optimal P_{opt} such that the minimal ppd throughout the perimeter is maximized

$$p_{opt} = \underset{0 \le p \le 1}{\operatorname{argmax}} \{ \min_{1 \le i \le d-1} f_i(p) \}$$

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Cont.

- Lemma 1: *given* ***p***, *func* ***ppd_i (R_a)*** *for const* ***t*** *&* ***R_a*** *@ segment s_0 is montoic decreasing func.*
  - *As distance b/n a robot & a segment* ↑ *probability of arriving in it during t time units decrease*
- Lemma 2*: if distance between two consecutive robots is smaller, the ppd in each segment is higher & vice versa*

Cont.

- Lemma 3: *team of k mobile robots in mission maximizes minimal ppd if:*

   a. *The time distance b/n every two consecutive robot is equal*
   b. *The robots are coordinated:*
      - *Move in the some dxn*
      - *All change dxn @ the some time*

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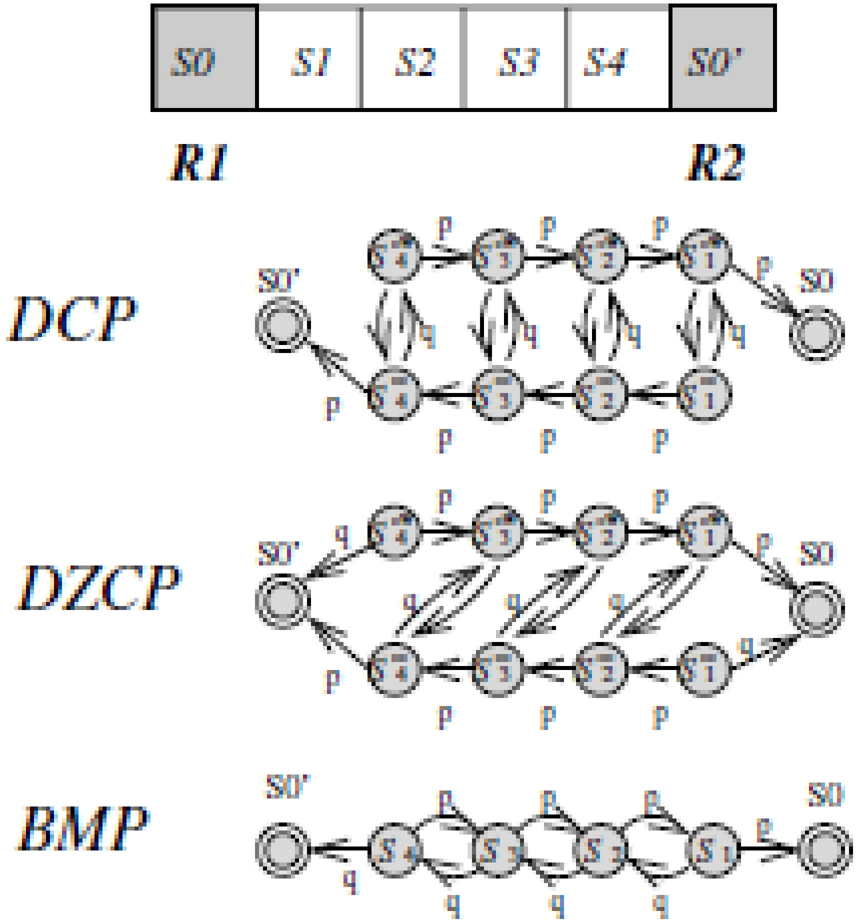
Algorithm to find p_{opt}

- 1st find the detection probability in each segment
- 2nd manipulate these equations to find p_{opt} (maxmin point)
- Complexity of algorithm is in polynomial time

Finding the equation



Cont.

- p of reaching a certain state in time ***r*** is the sum of probabilities of reaching in state s_j multiplied by p of being in state s_j @ time **r-1**

Cont.

Procedure FindFunc(d, t)

For each $s_{init} = s_i \in \{s_1, \ldots, s_{d-1}\}$ do:

Create matrix M of size $(2d + 2) \times (t + 1)$, initialized with 0s.

Set $M_0(s_{init}) \leftarrow 1$.

Complete M gradually using the following rules.

1) **For** each entry $M_r(s_i^{cw})$ set value to $p \cdot M_{r-1}(s_{i+1}^{cw}) + q \cdot M_{r-1}(s_i^{cc})$.
2) **For** each entry $M_r(s_i^{cc})$ set value to $p \cdot M_{r-1}(s_{i-1}^{cc}) + q \cdot M_{r-1}(s_i^{cw})$.
3) **For** absorbing states, set entry $M_r(s_{abs}) = M_{r-1}(s_{abs}) + p \cdot [M_{r-1}(s_1^{cw}) + M_{r-1}(s_d^{cc})]$.

Report row t of M.

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Cont.

- Time complexity:
  - FindFunc is d.(2d+2).(t+1). Since t is bounded by d-1 & d=N/k
  - ➔ complexity is $O((N/k)^3)$

- Next find maxmin point
  - Is the value that lies inside the intersection of the all integrals of $\boldsymbol{f_i}$

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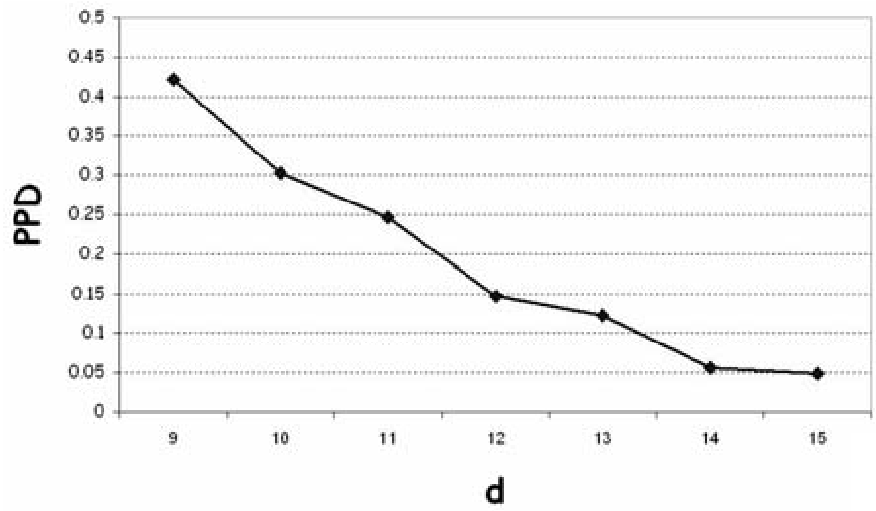
Algorithm 2

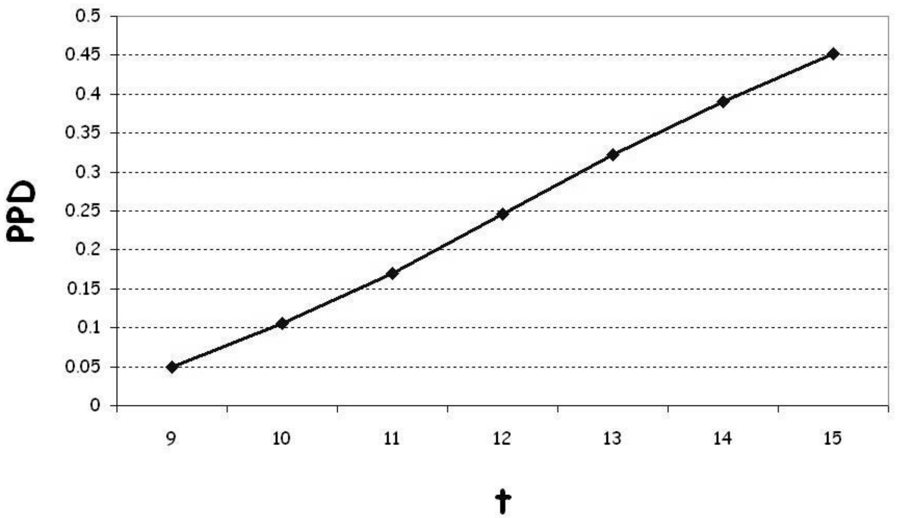
Algorithm FindP(d, t)

1) $F \leftarrow$ Procedure FindFunc(d, t).
2) Set $p_{opt} \leftarrow 0$.
3) **For** $F_{pivot} \leftarrow F_{1,\ldots,d-1}$ **do:**
   a) Compute local maxima $(p_{max}, F_{pivot}(p_{max}))$ of F_{pivot} in the range $(0, 1)$.
   b) **For** each F_i, $1 \leq i \leq d-1$, compute intersection point p_i of F_i and F_{pivot} in the range $(0, 1)$.
   c) If $F_{pivot}(p_i) > F_{pivot}(p_{max})$ and $F_{pivot}(p_i) \leq F_k(p_i) \forall k$, then $p_{opt} \leftarrow p_i$.
   d) If $F_{pivot}(p_{max}) > F_{pivot}(p_i)$ and $F_{pivot}(p_i) \leq F_k(p_i) \forall k$, then set $p_{opt} \leftarrow p_{max}$.
4) Return $(p_{max}, F_{pivot}(p_{max}))$.

Result



PPD
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
9
10
11
12
13
14
15
d



PPD
0.5
0.45
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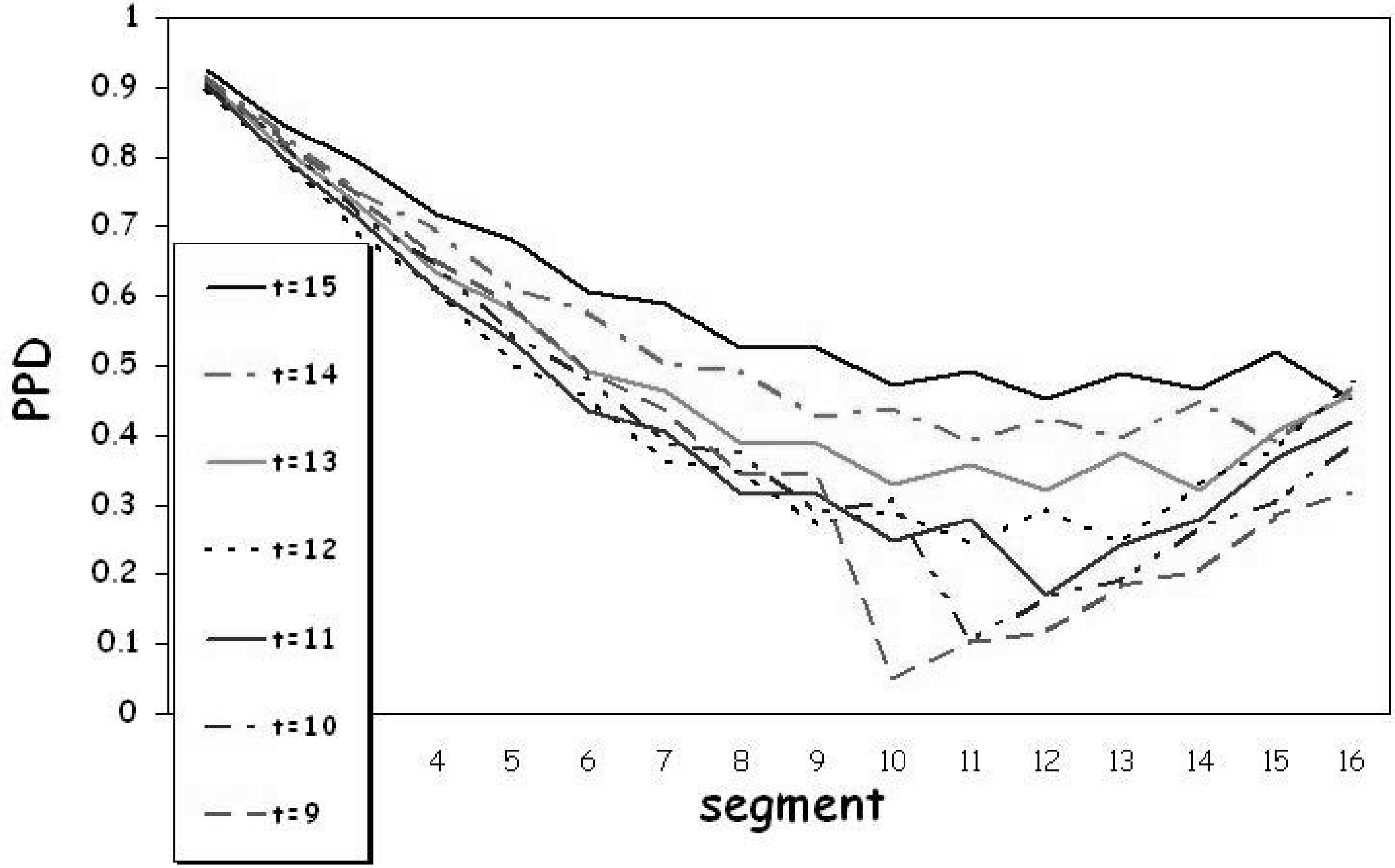
Cont.



PPD
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
t:15
t:14
t:13
t:12
t:11
t:10
t:9
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11
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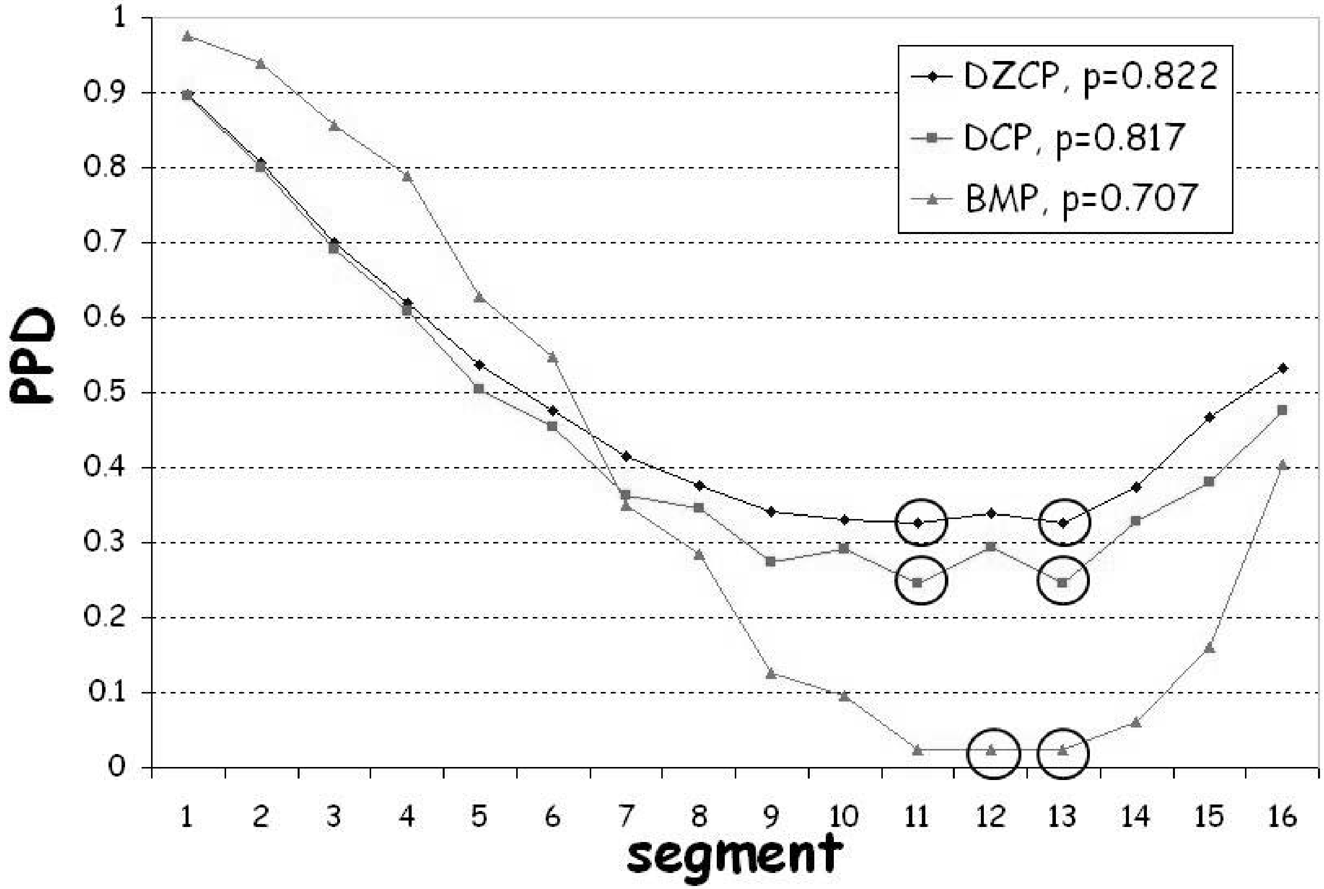
13
14
15
16
segment

Cont.



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Conclusion and future work

- Non- deterministic algorithm under strong adversary
- Polynomial time complexity

- Continuous case rather than discrete model
- More realistic movement models
  - With arbitrary tuning time

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Cont.

- Other adversarial models
- Case of unknown adversary similar to Bayesian games
- Adopt this algorithm in other domains
    - e.g. Area patrol

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