Multi-Agent Adversarial Games in Partially Observable Euclidean Space

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Two Related Problem Domains

- Two problems that involve adversarial groups of agents maneuvering in Euclidean space
  - » Neither of them is *exactly* moving-target defense
  - » But both of them are closely related to it

1. Tracking and evasion

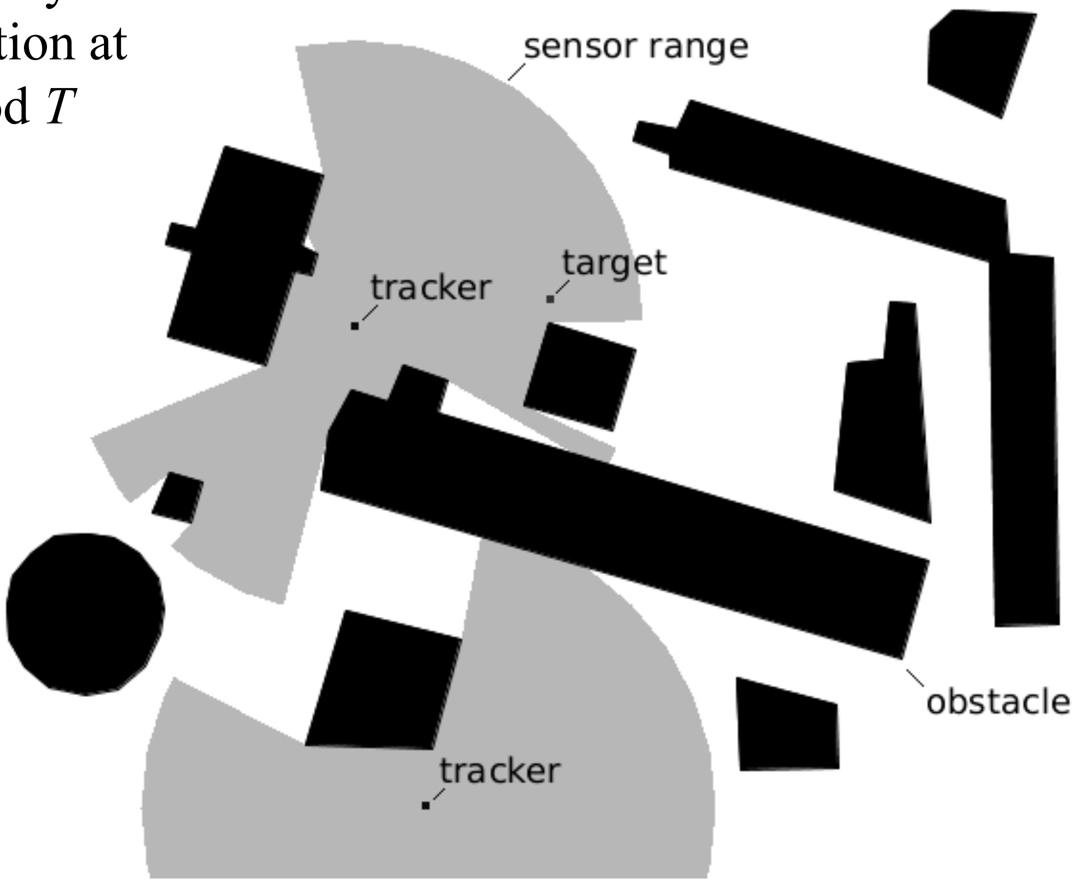
   Team of *tracker* agents want to track the location
   of an intelligent *target* agent
   that wants to evade their surveillance

2. Naval asset protection

   Team of patrolling/blocking agents want to protect
   assets against intelligent intruders

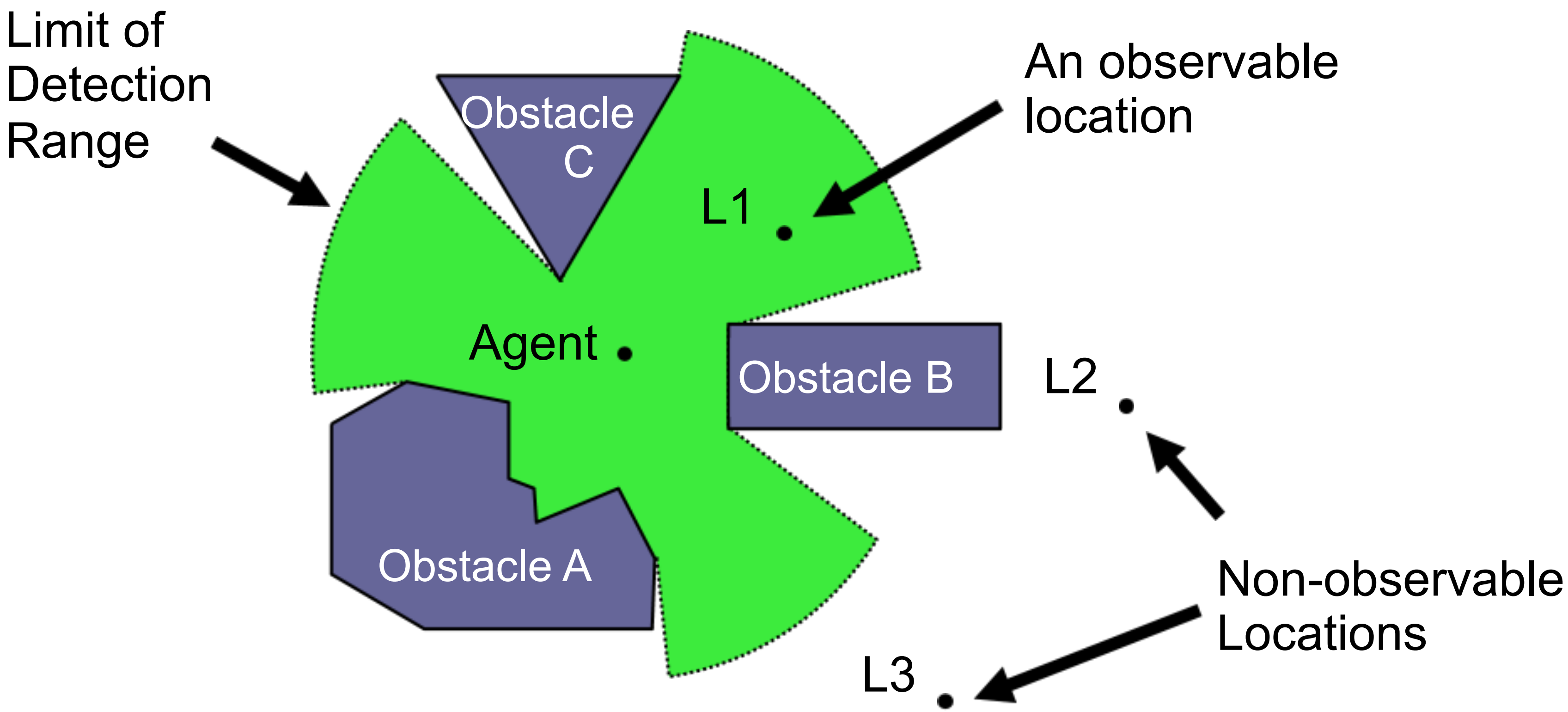
Part 1. Tracking and Evasion

- Team of cooperating tracker agents
  - Want to minimize uncertainty about a target agent's location at the end of some time period *T*
- Target agent
  - Wants the opposite
- Continuous Euclidean space
  - Arbitrarily shaped polygonal obstacles
- Partially observable
  - …



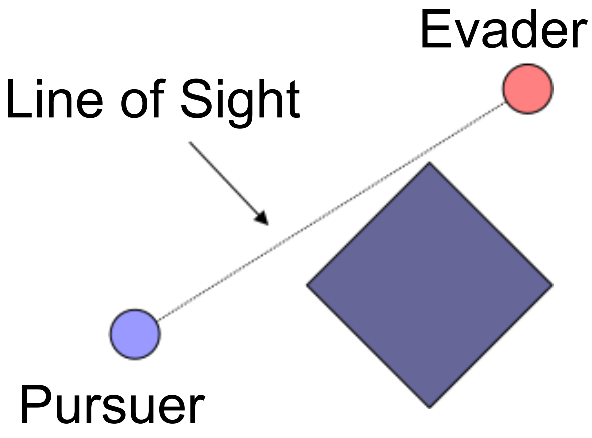
Partial Observability

- Agents' observation capabilities are limited by
  - sensor range
  - obstacles

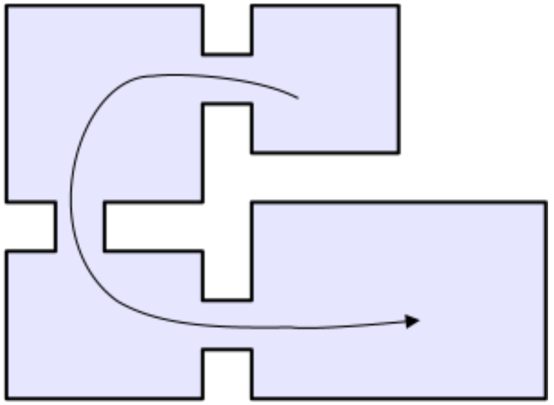


Related Work

- Maintain line-of-sight on the target
  - » Game ends when visibility is lost
  - » Perfect-information game
  - » Differential game theory



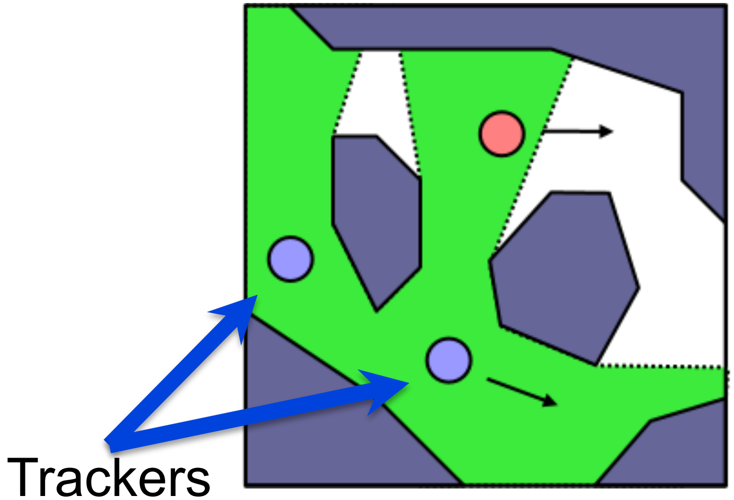
- Find an unseen intruder (hider-seeker)
  - » Game ends when target is discovered
  - » Combinatorial search to generate patrol strategies
  - » Computed offline
  - » No pursuit strategy



Need for New Techniques

- Can we just combine existing techniques?
  - Not effectively, for two reasons

- Our objective is different
  - Minimize uncertainty about the target's location, even when the target isn't visible
  - Sometimes the most effective strategy is to to choose actions that sacrifice visibility,
    - in order to reduce uncertainty later on

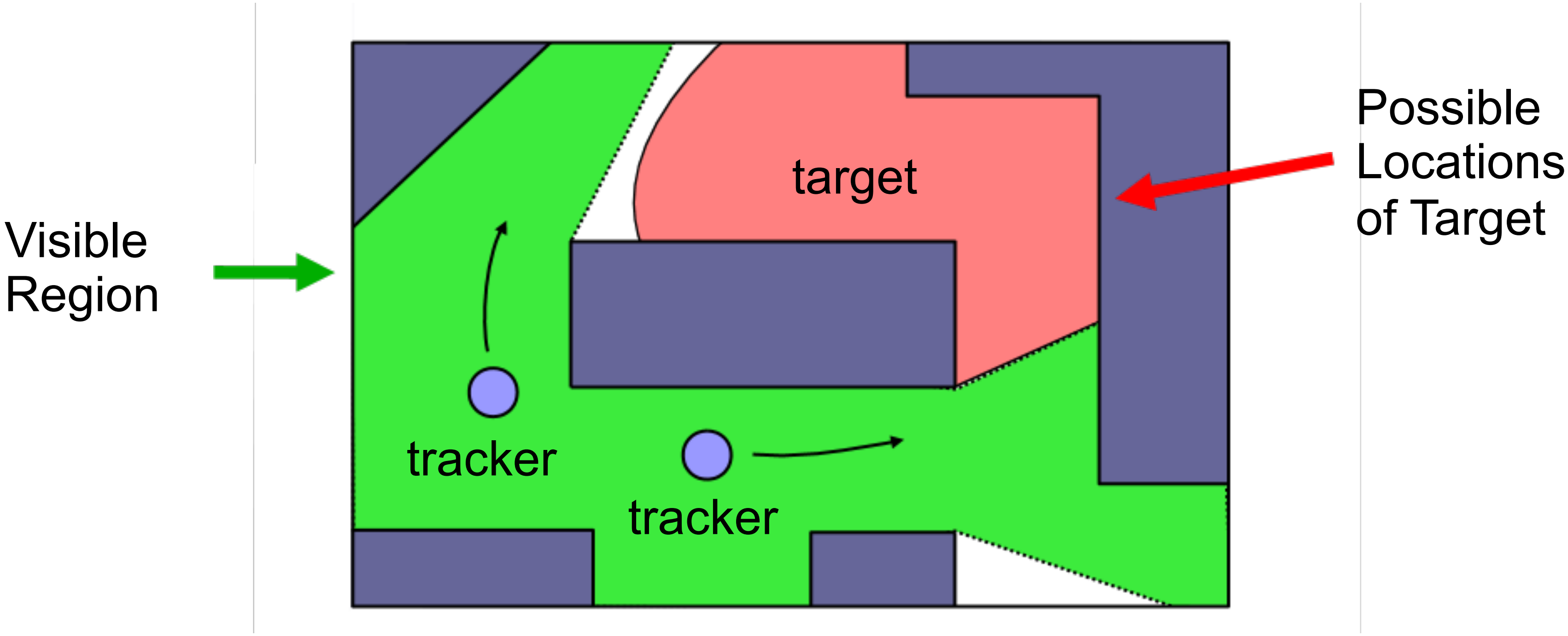


Move out of sight of the target, in order to regain visibility later

- Need to generate strategies quickly, in response to target's movement
  - Rules out many techniques that are based on deep combinatorial search

Minimizing Uncertainty

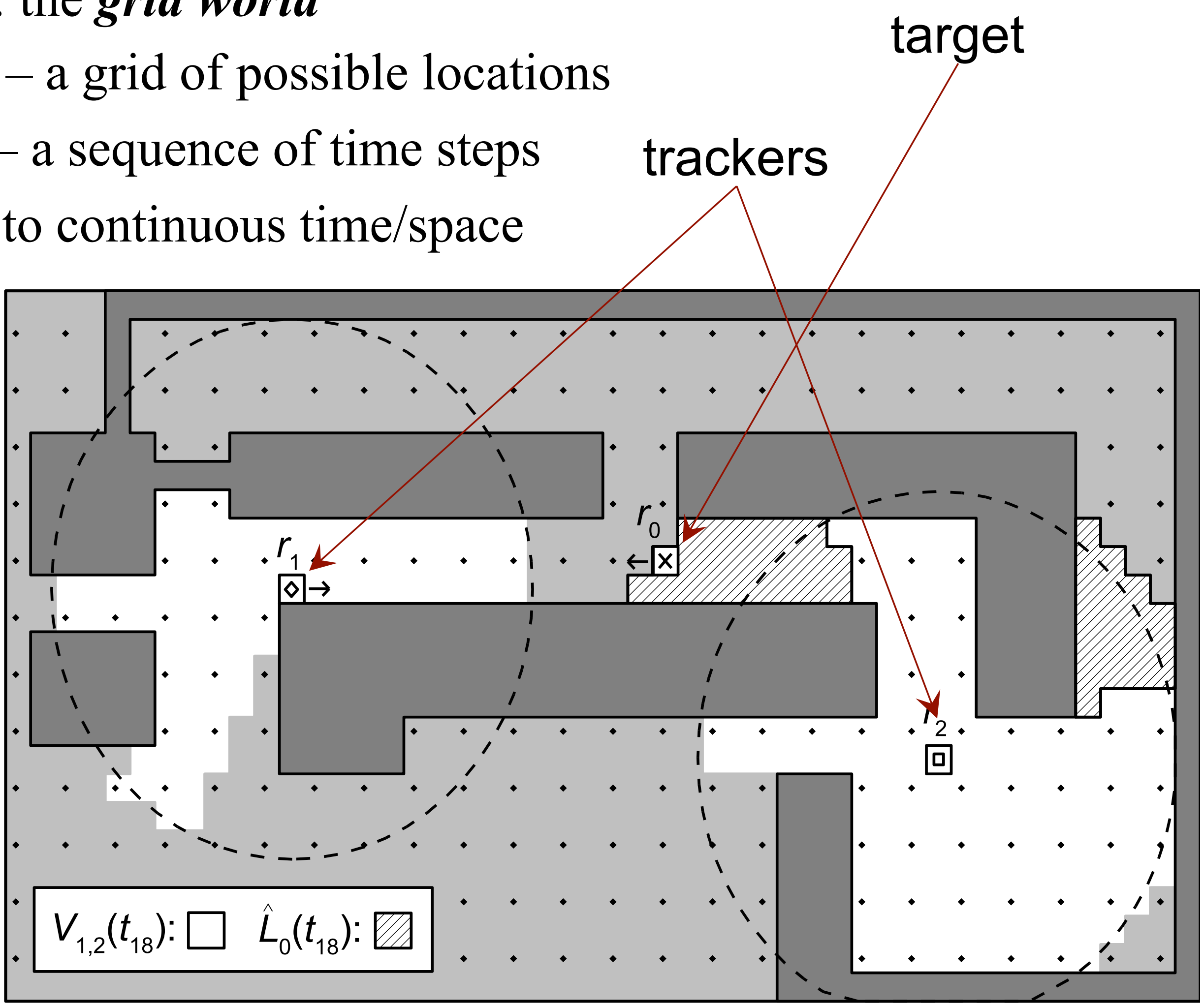
- Loss of visibility of the target may be inevitable
- But with the right strategy, the trackers may be able to
  - Guarantee that the target is within some small region
  - Recover visibility later on



Part 1(a). Earlier Work

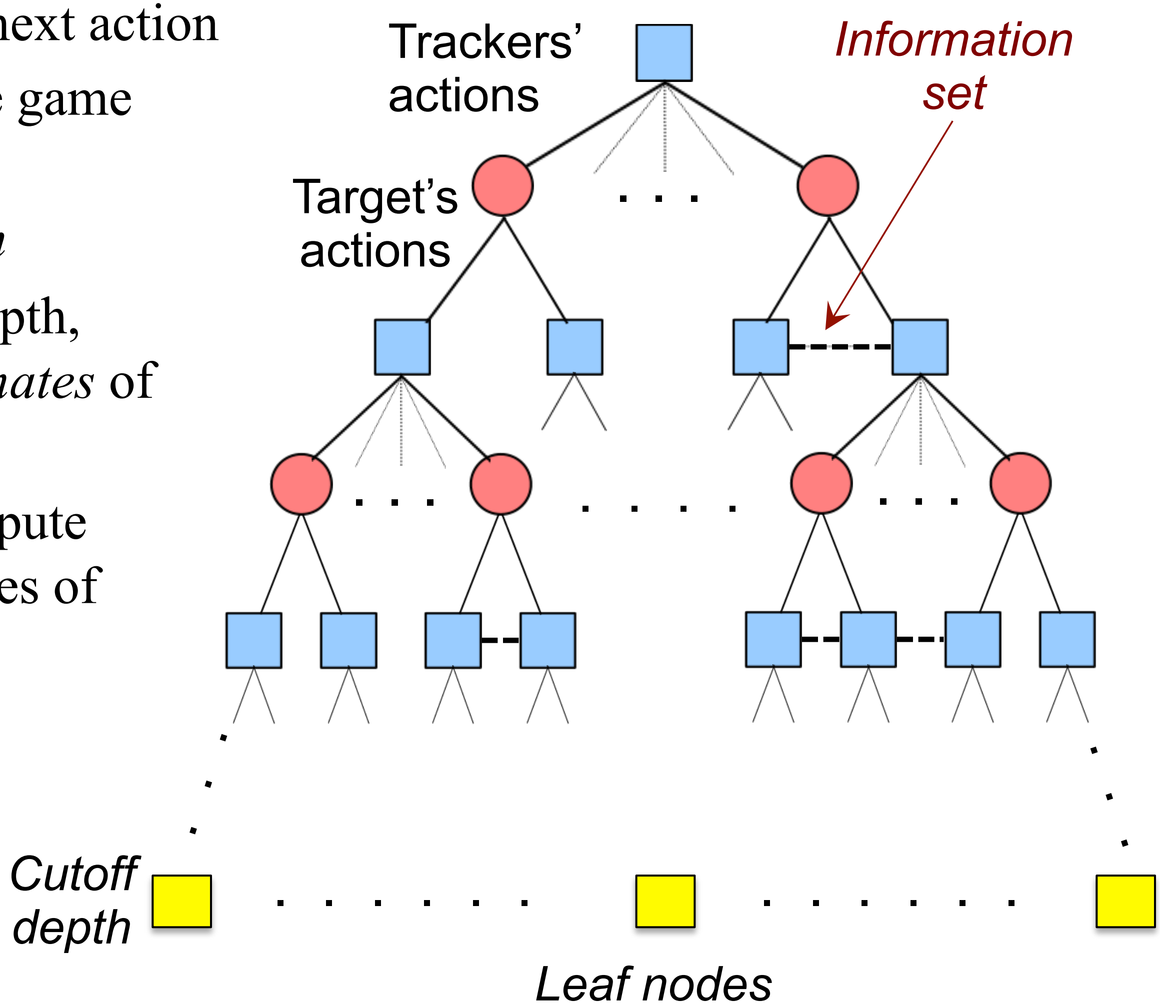
E. Raboin, D. Nau, U. Kuter, S. K. Gupta, and P. Švec. Strategy generation in multi-agent imperfect-information pursuit games. In *Ninth Internat. Conf. on Autonomous Agents and Multiagent Systems (AAMAS)*, 2010. pdf.

- Imperfect-information zero-sum extensive-form game
- Simplifying assumption: the ***grid world***
  - Space is discrete – a grid of possible locations
  - Time is discrete – a sequence of time steps
    - » Later I'll generalize to continuous time/space
- Agent's possible actions at each time step:
  - » Move to any adjacent grid point that isn't occupied by an obstacle



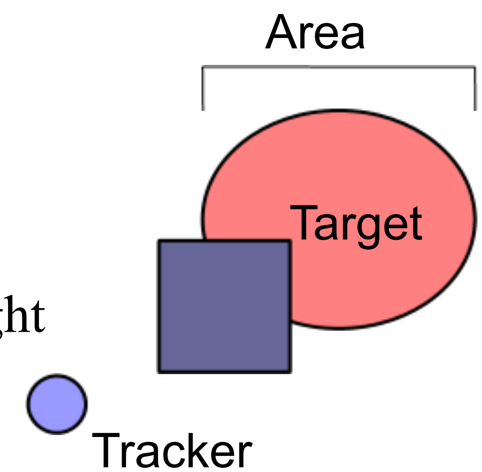
Grid-World Game Tree Search

- Imperfect-information game tree
- Search algorithm to select next action
  - Run it repeatedly as the game progresses
- Search to some *cutoff depth*
  - For the nodes at that depth, compute *heuristic estimates* of their utility values
- Use those estimates to compute estimates of the utility values of the nodes higher in the tree
  - At the top level, choose the action that looks best

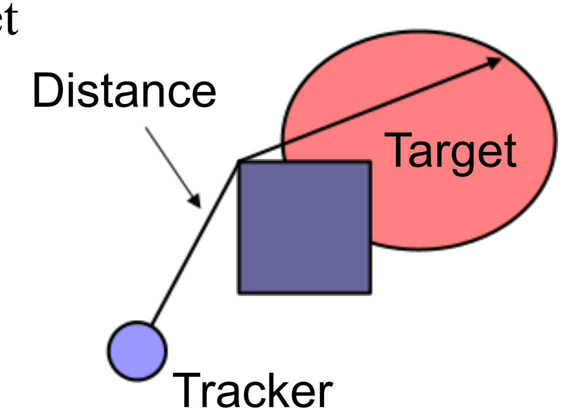


Evaluation Functions

- A ***heuristic evaluation function*** is what's used to estimate the utility values of the leaf nodes



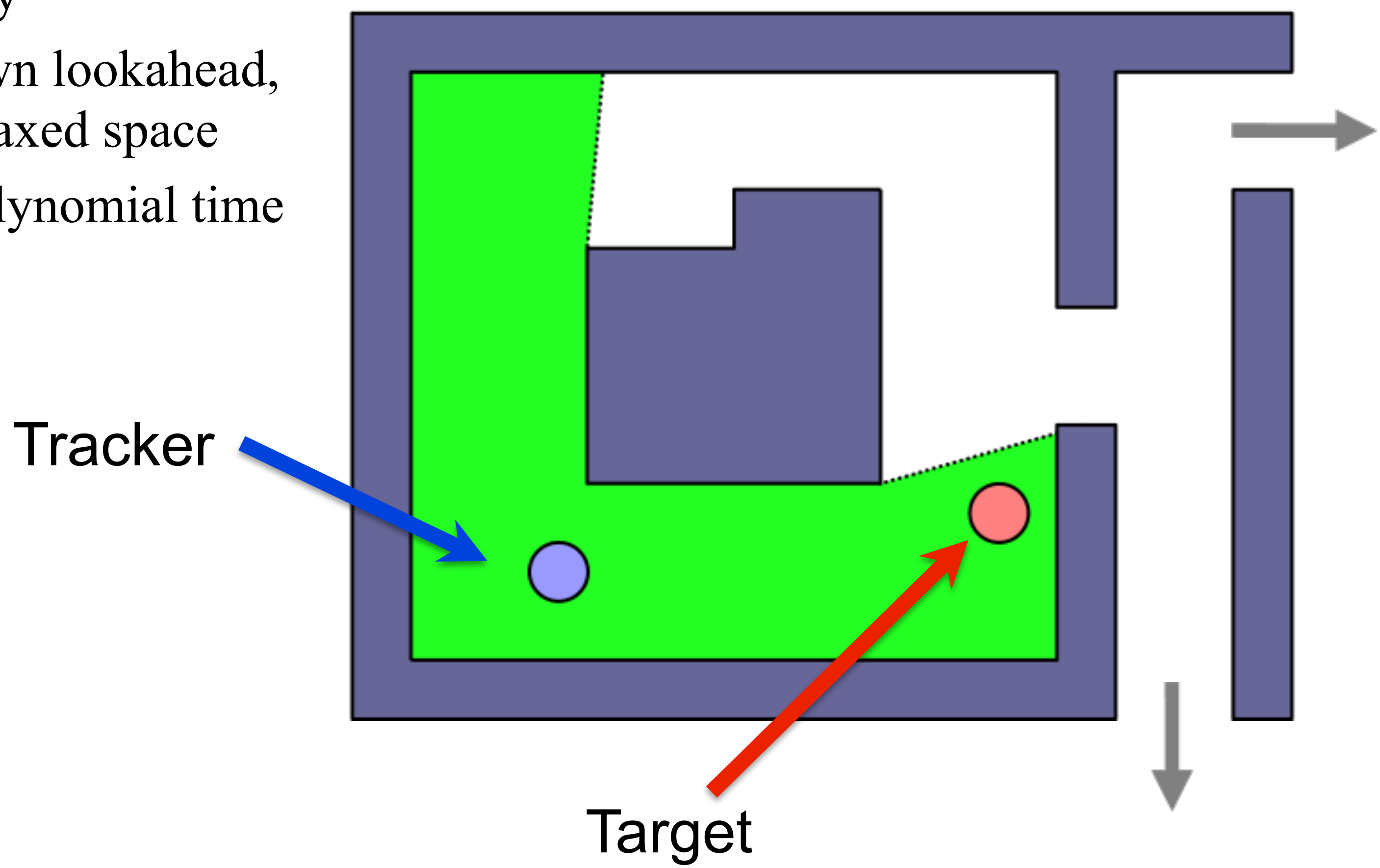
- Some simple ***local heuristics***:
  - » **Region Size (RS)**:
    - size of the region where the target might be located
  - » **Max Distance (MD)**:
    - maximum possible distance to the target



- But we can do better …

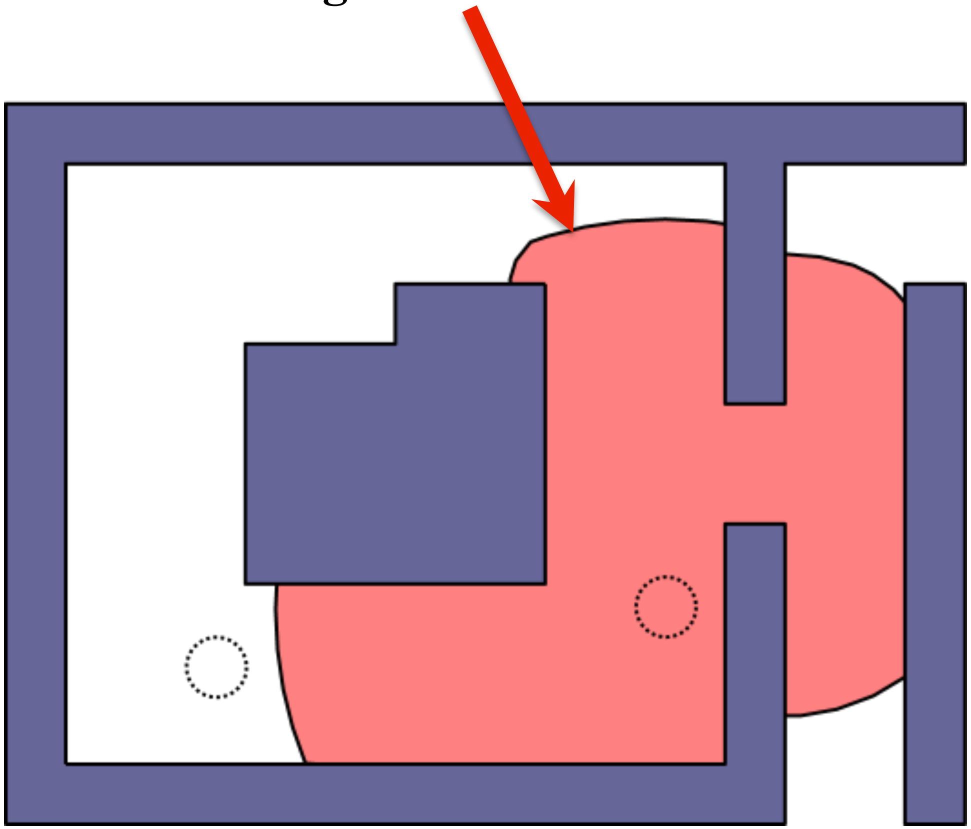
Predicting Loss of Visibility

- Heuristic algorithm to predict loss of visibility
  - » Does its own lookahead, but in a relaxed space
  - » Runs in polynomial time



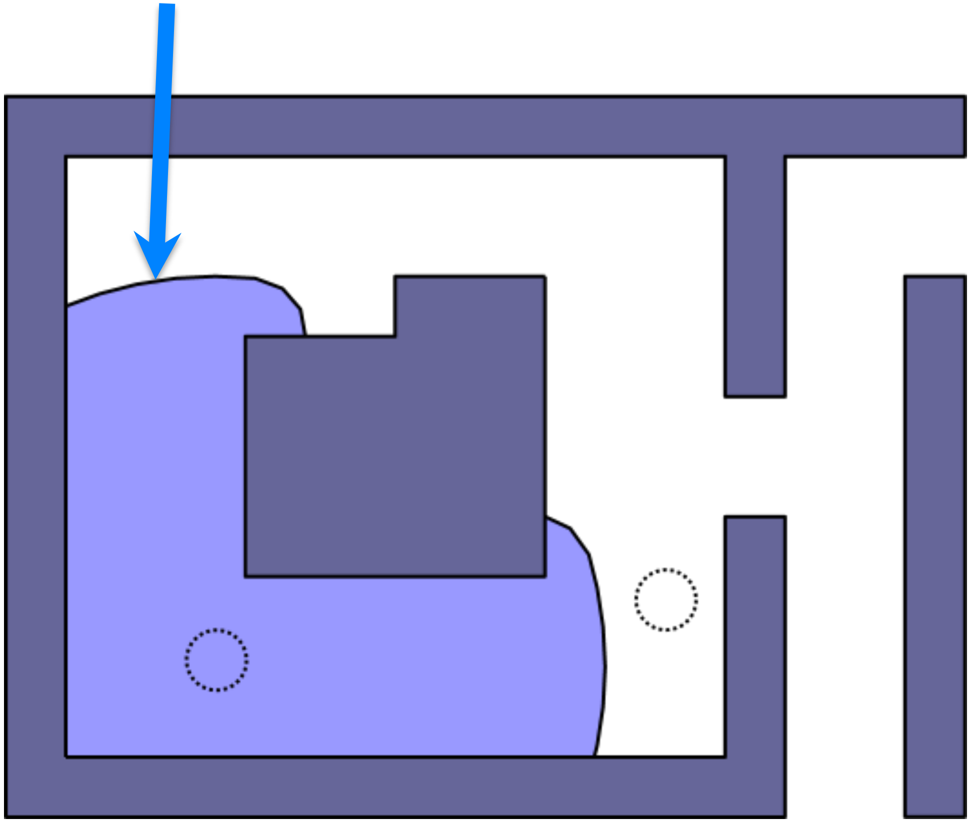
Predicting Loss of Visibility

- Set of locations that it's possible for the **target** to reach in time *t*



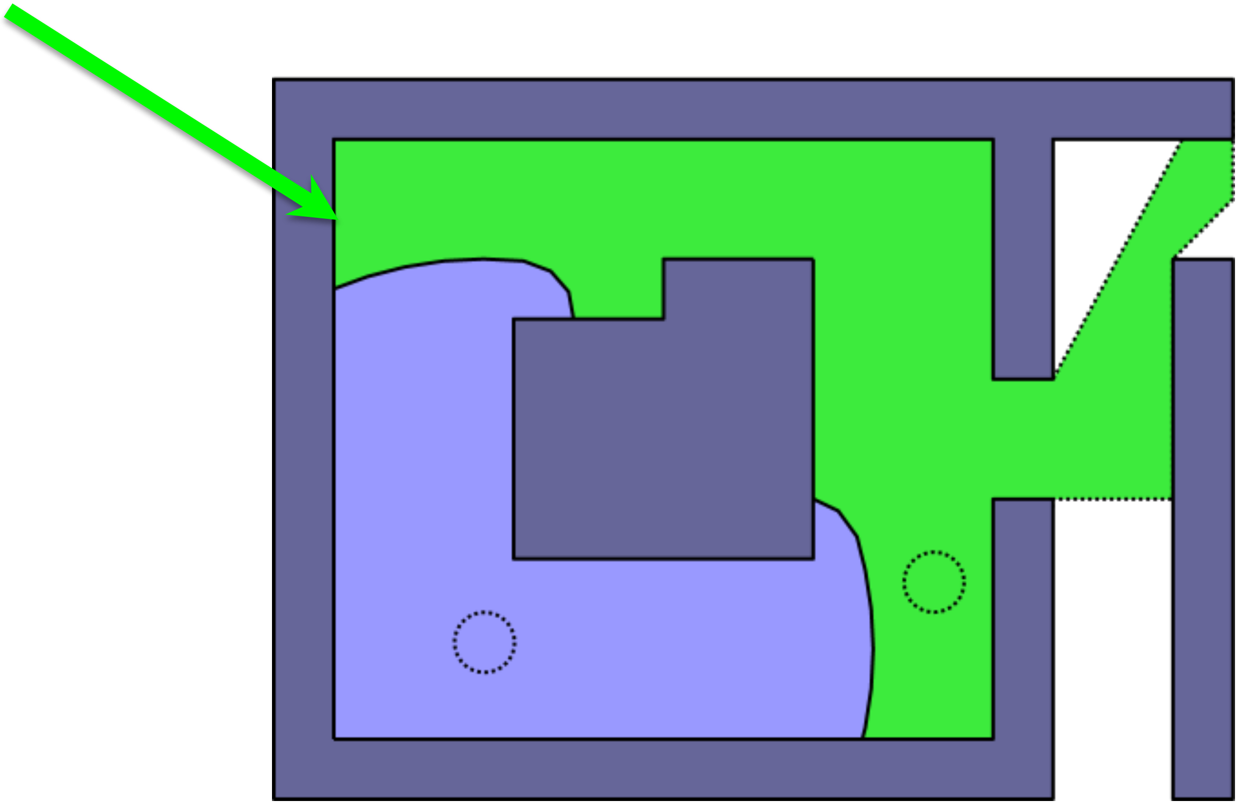
Predicting Loss of Visibility

- Set of locations the **tracker** can reach in time *t*



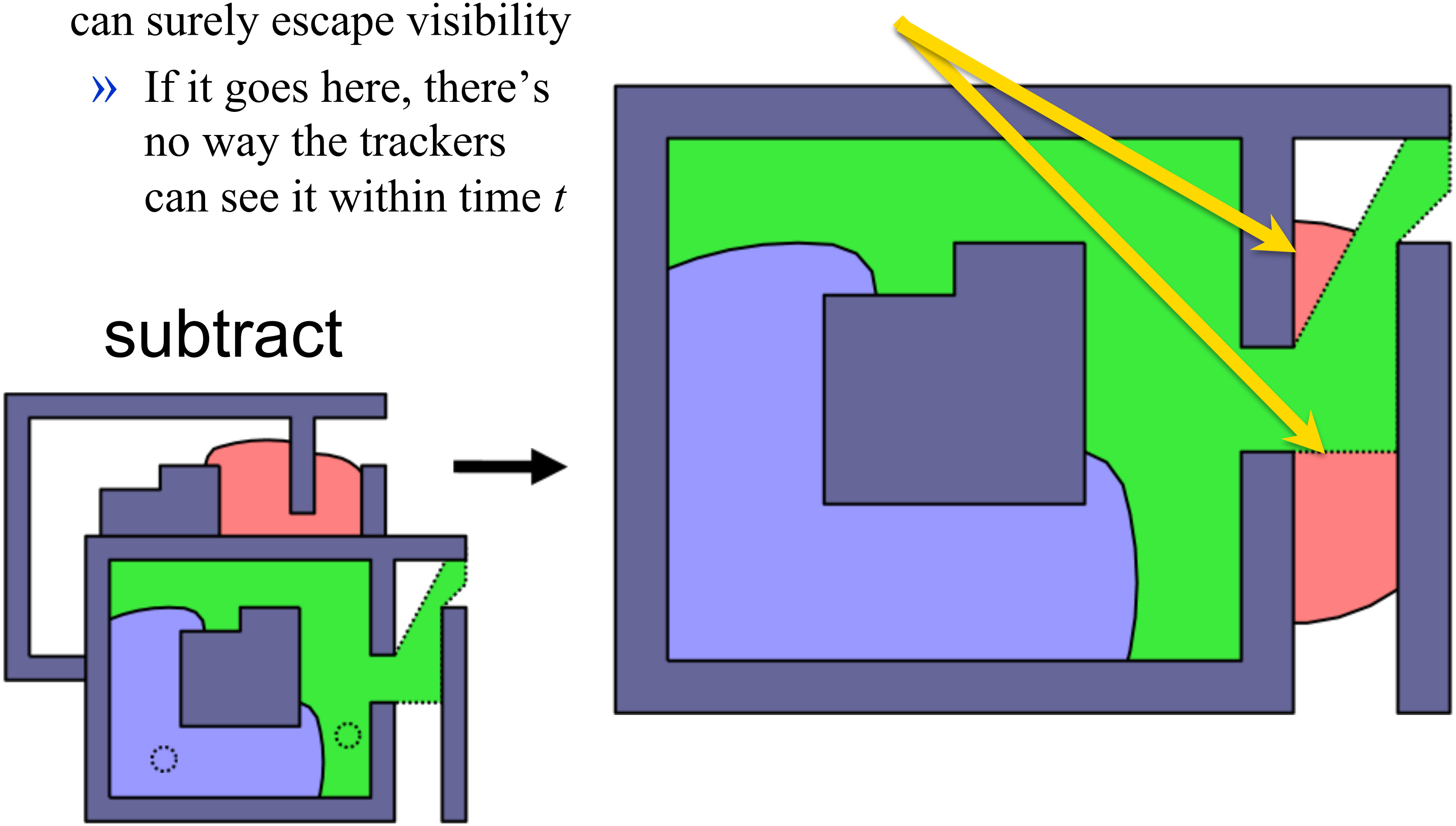
Predicting Loss of Visibility

- Locations that are **visible** from locations the tracker can reach by time *t*



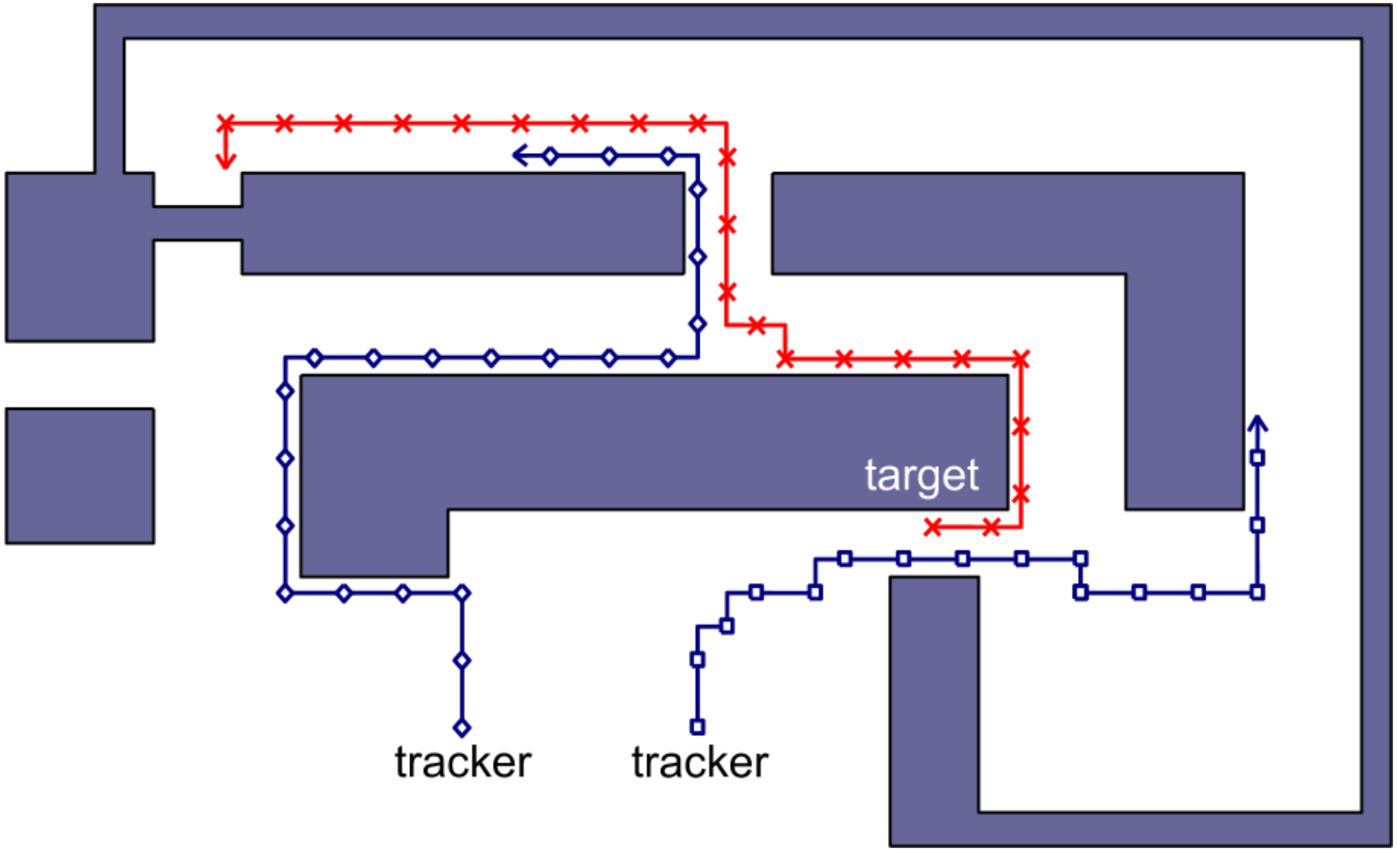
Predicting Loss of Visibility

- **Relaxed Lookahead (RLA)** heuristic: size of the region where the target can surely escape visibility
  - If it goes here, there's no way the trackers can see it within time *t*



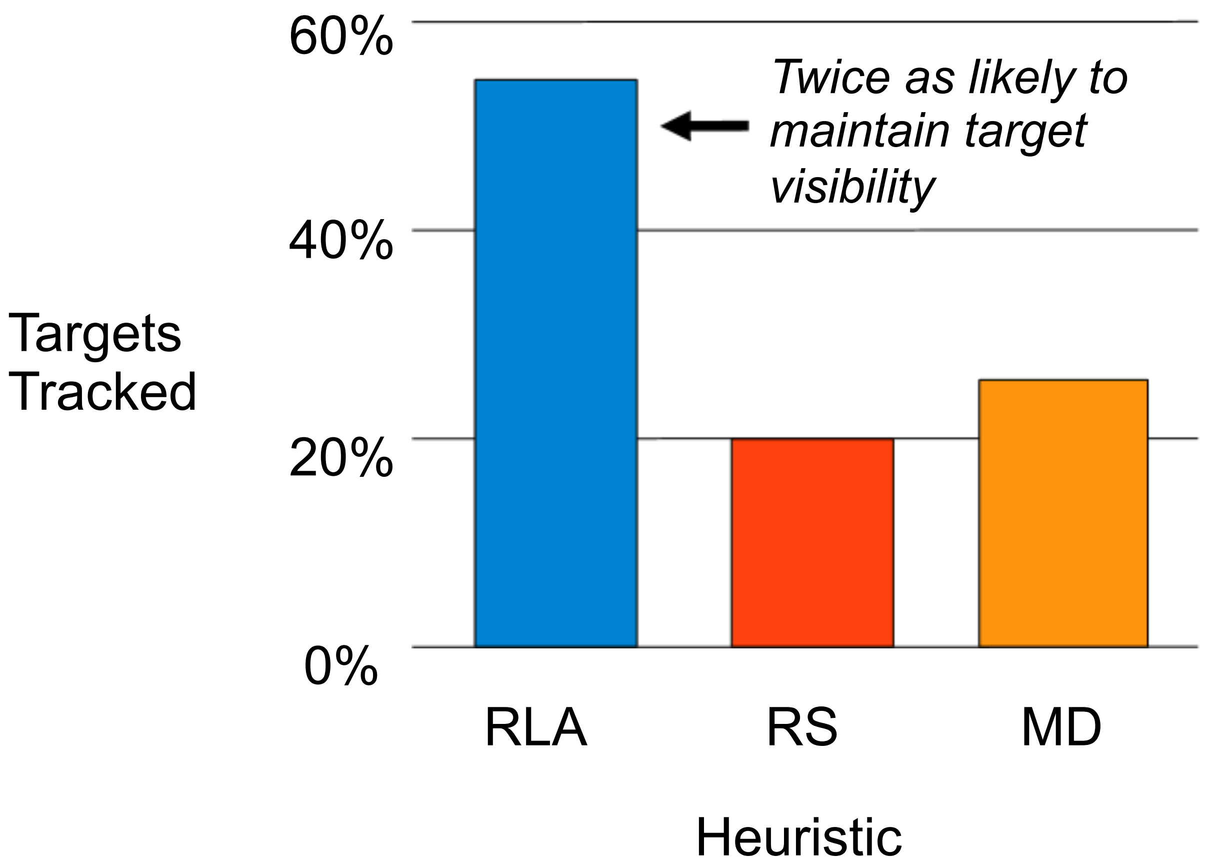
Performance

- RLA can be computed very quickly
- It produces significantly better strategies than the local heuristics



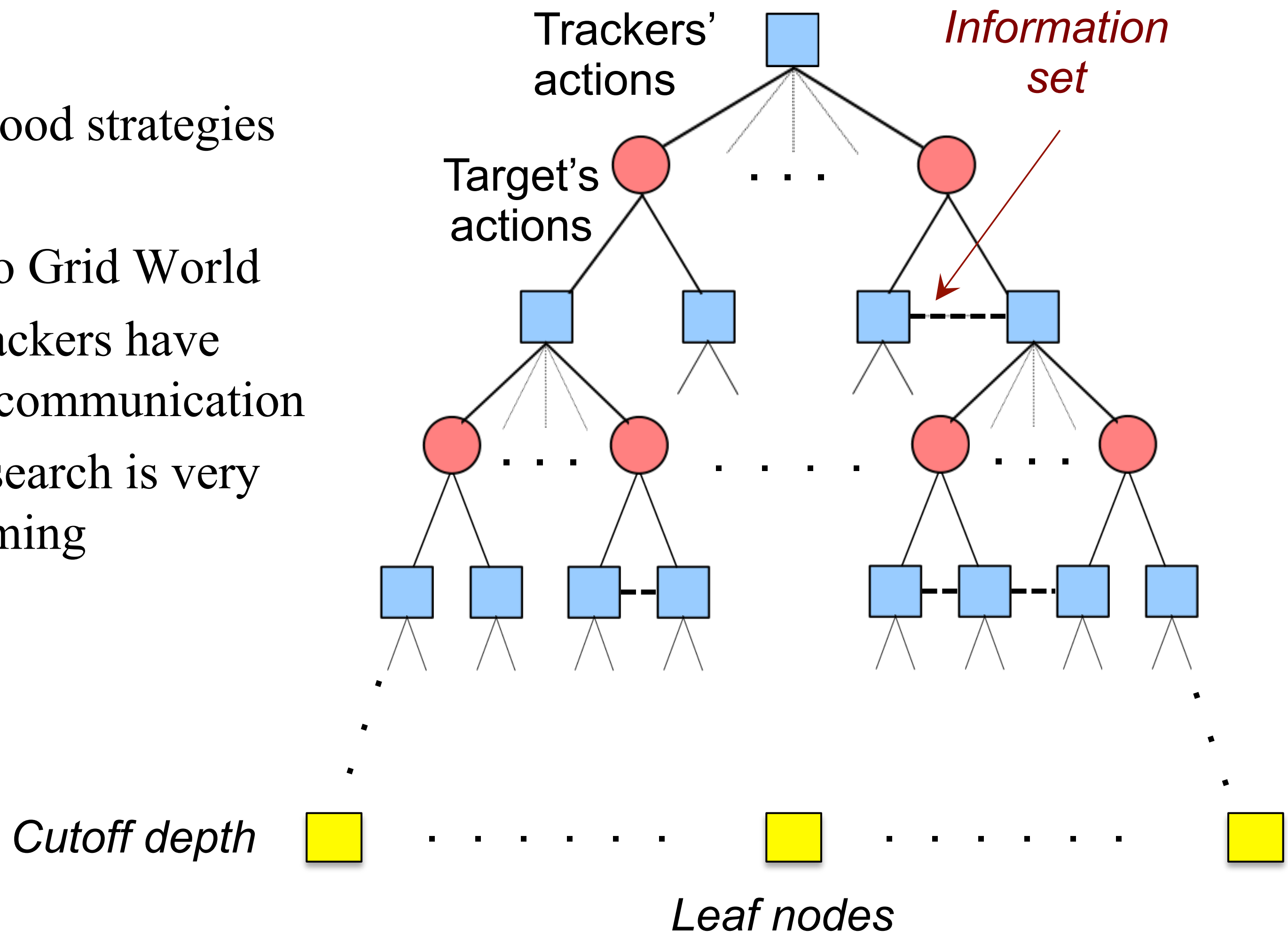
Experimental Results

- Two tracker agents, one target agent
- Three heuristics: RLA, Max Distance, Region Size
- 500 randomly generated trials



Advantages and Disadvantages

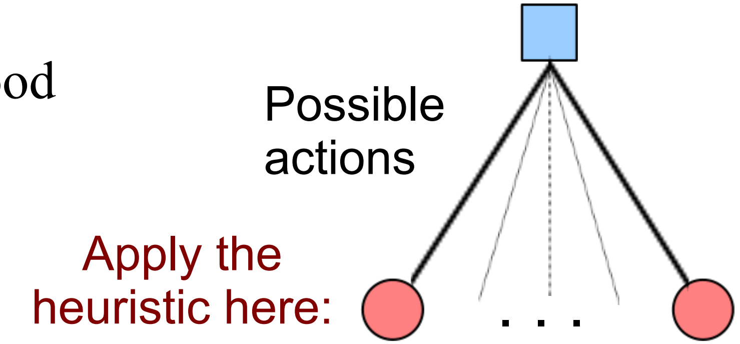
- Advantage:
  - Generates good strategies
- Disadvantages:
  - Restricted to Grid World
  - Assumes trackers have continuous communication
  - Game-tree search is very time-consuming



Part 1(b). Later Work

E. Raboin, D. Nau, and U. Kuter. Generating strategies for multi-agent pursuit-evasion games in partially observable Euclidean space. In *Autonomous Robots and Multirobot Systems (ARMS) Workshop*, 2012. pdf.

- Observations
  - The game-tree search is more-or-less superfluous
  - If we apply RLA directly to the available actions
    - i.e., depth-1 search
    - We get strategies that are nearly as good
    - We get them **much** more quickly

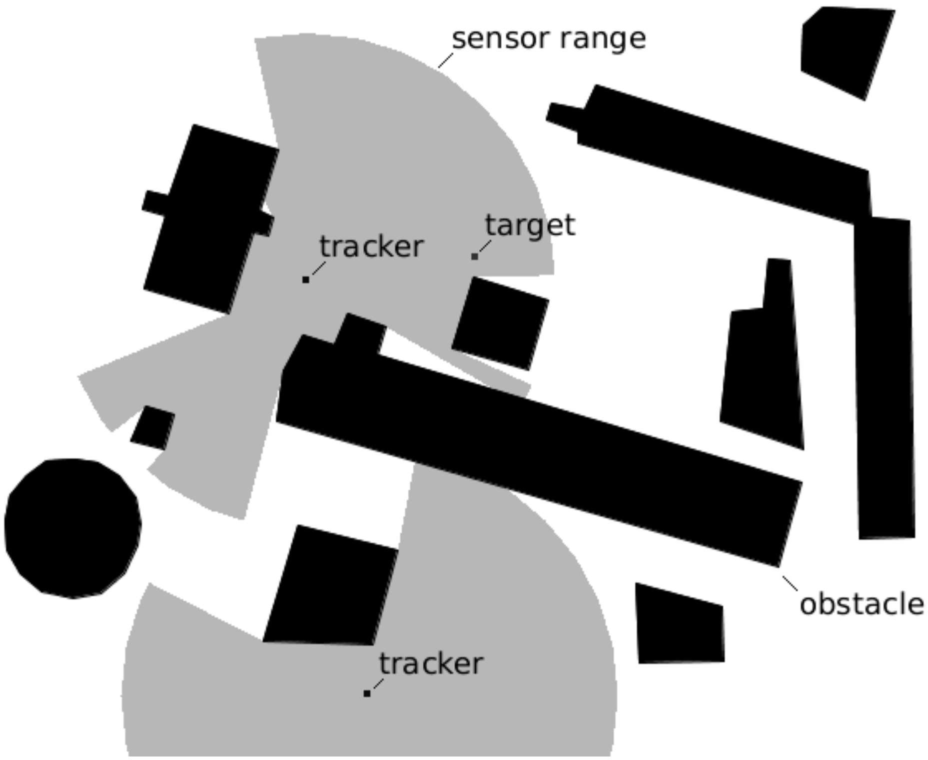


- Thus:
  - Develop a heuristic similar to RLA, but for continuous Euclidean space
  - Design it to be tolerant of interruptions in communication
  - Use it directly, rather than doing a game-tree search

The LEL Heuristic

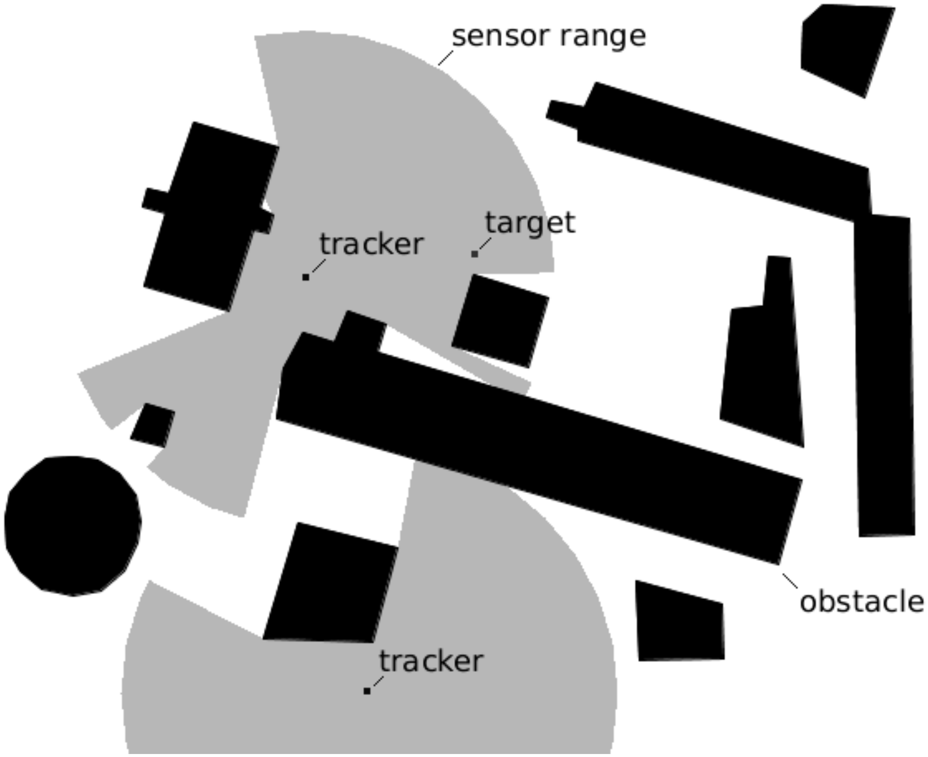
- **LEL**: **L**imited-communication **E**uclidean-space **L**ookahead

- Notation:
  - » Agents $a_0, a_1, \ldots, a_n$,
    - a_0 is the target
    - $a_1, \ldots, a_n$ are the trackers
  - » A location l is **hidden** at time t if no agent will be able to reach, by time t, a location from which l can be observed



- In principle, we want this:
  - » LEL = {area of the set of hidden locations that a_0 can reach by time t}
    averaged over some time interval}

Imperfect Information

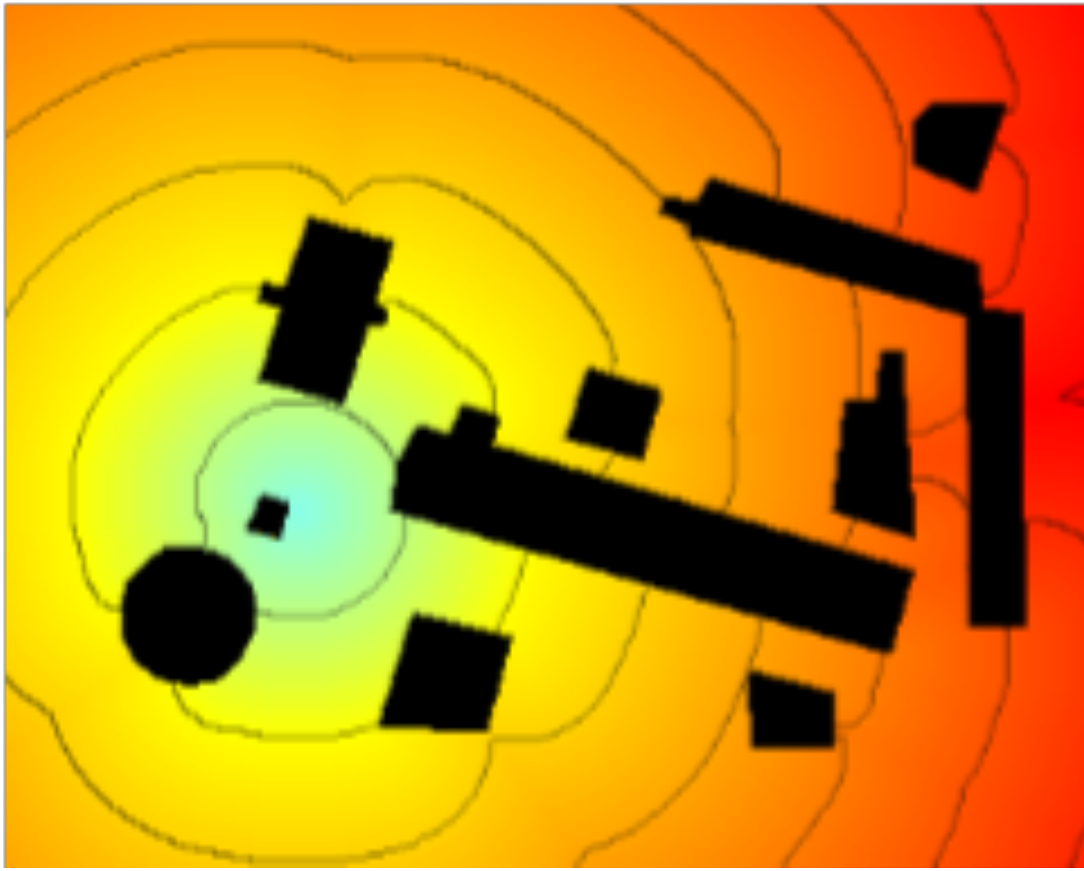


- We need to deal with **imperfect information**
  - » Limits on the sensor data that a_i can acquire directly
  - » Limits on the information that the other trackers can communicate to a_i
- For each tracker agent a_i, let

  O_i = {all observations available to a_i}
  = {observations a_i has made}
  ∪{all observations the other trackers have been able to send to a_i}
- Calculate values conditioned on O_i

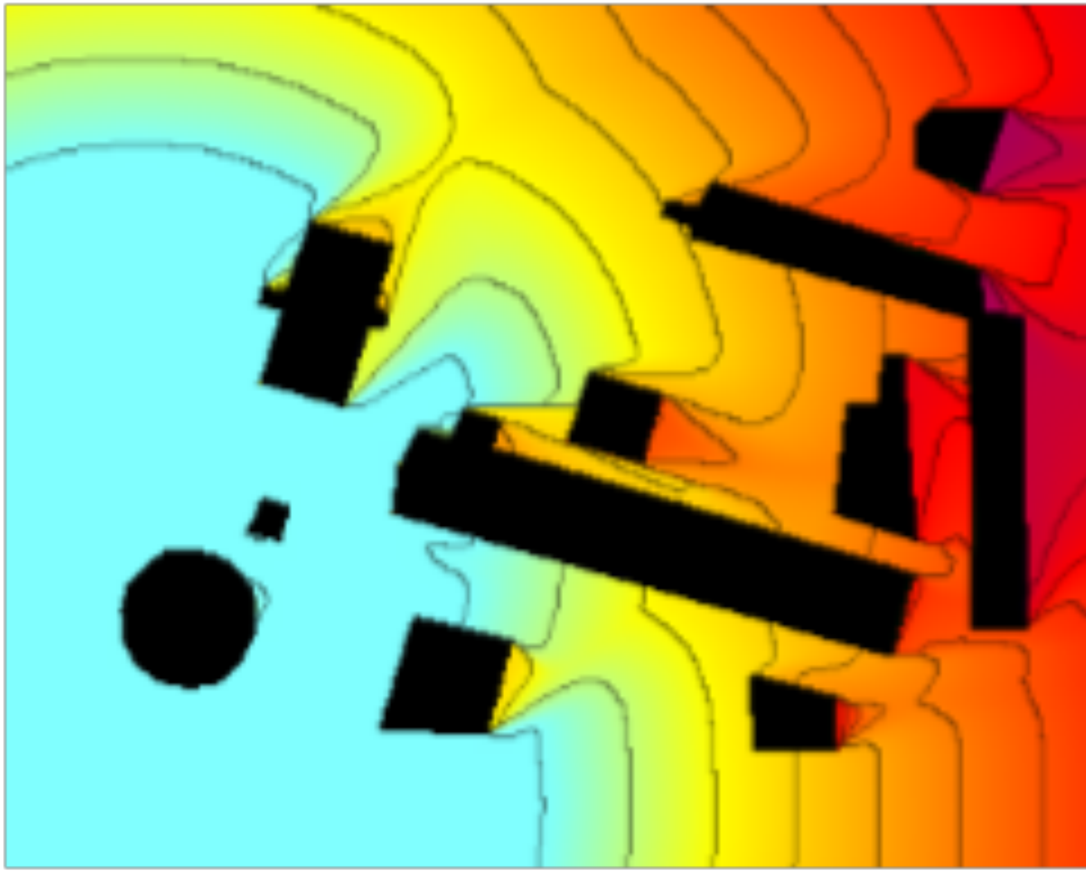
Locations the Target Might Reach

Reachable$(t \mid O_i)$
= {all locations that the **target** might be able to reach by time t, given O_i}



Heat graph:
color shows *Reachable*$(t \mid O_i)$
for increasing t

Locations the Trackers Might See



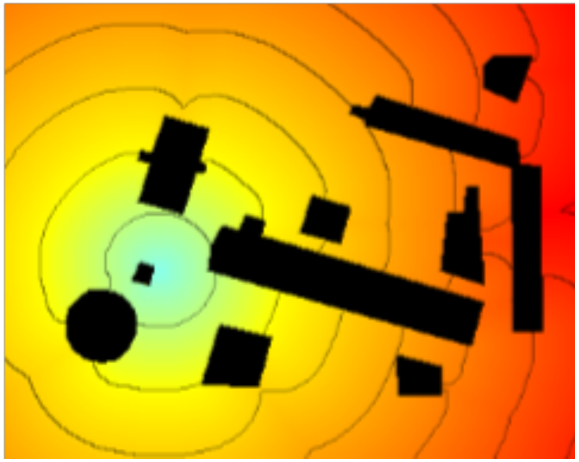
$Viewable(t \mid O_i)$

= {all locations that the **trackers** might be able to observe at time t, given O_i}

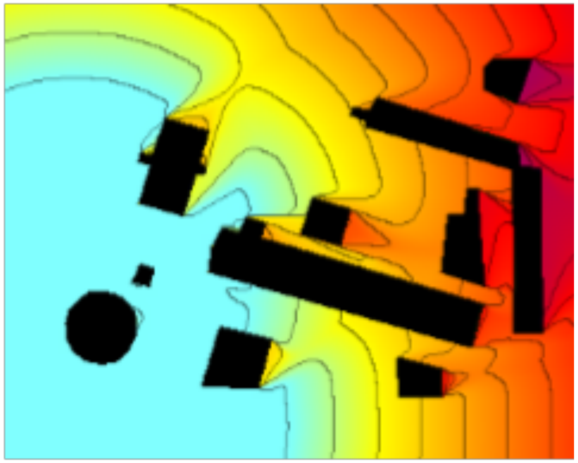
Heat graph:
color shows $Viewable(t \mid O_i)$
for increasing t

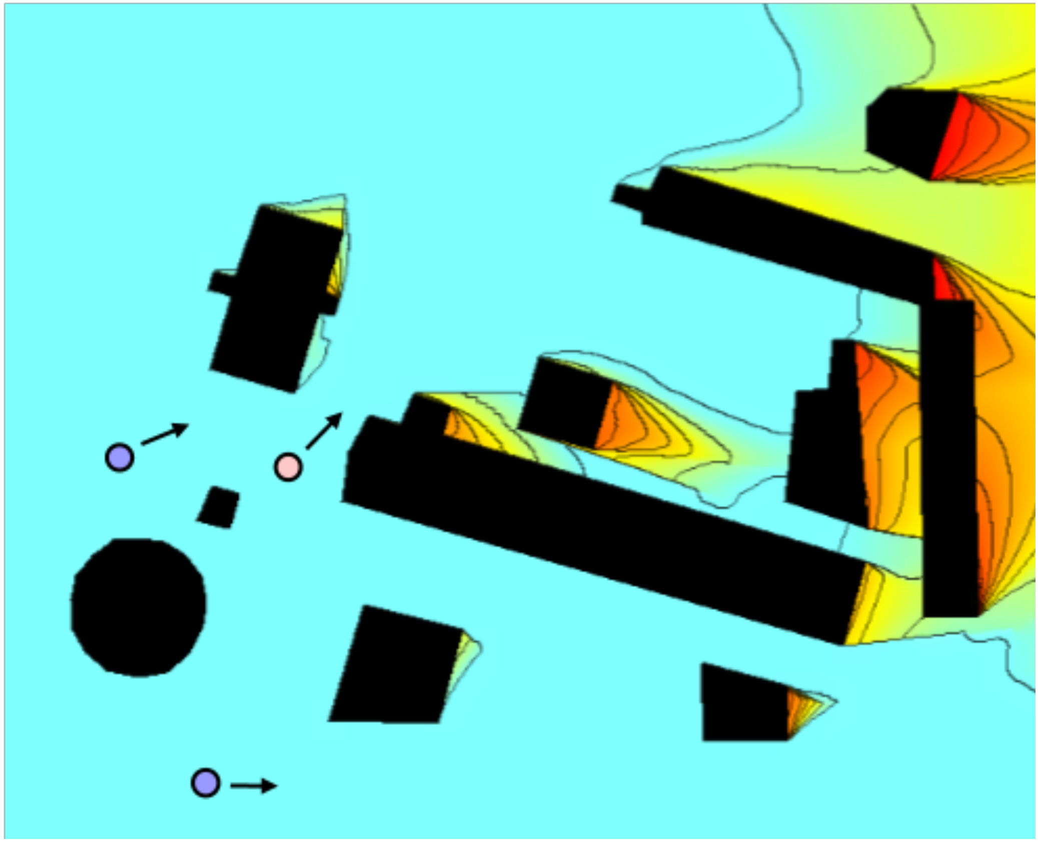
The LEL Heuristic

Reachable$(t \mid O_i)$



Viewable$(t \mid O_i)$





Heat graph:

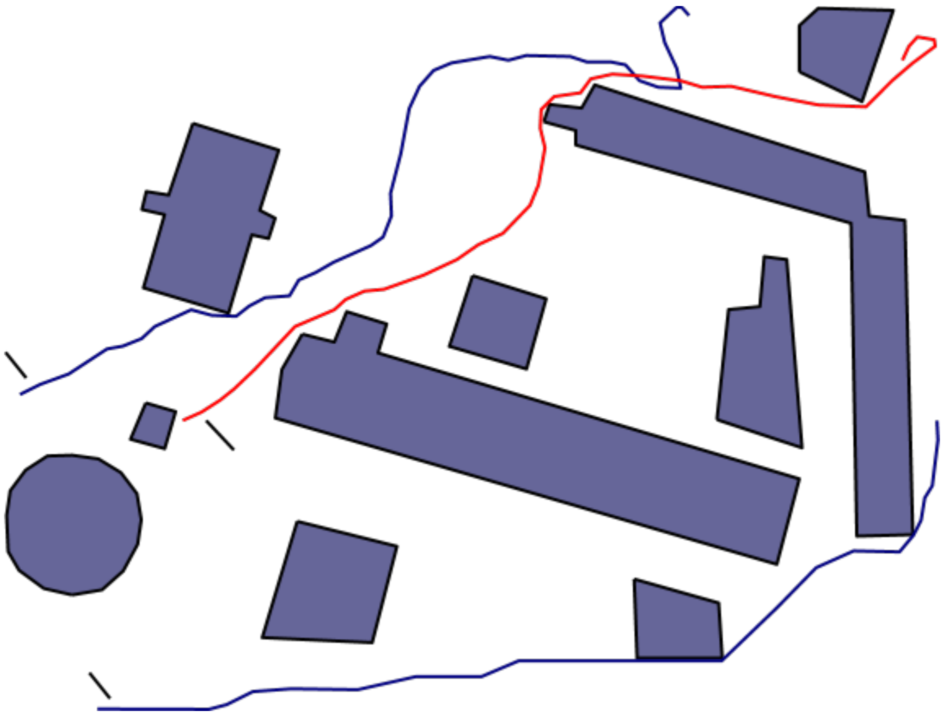
color shows *Reachable*$(t \mid O_i)$ – *Viewable*$(t \mid O_i)$ for increasing t

LEL =

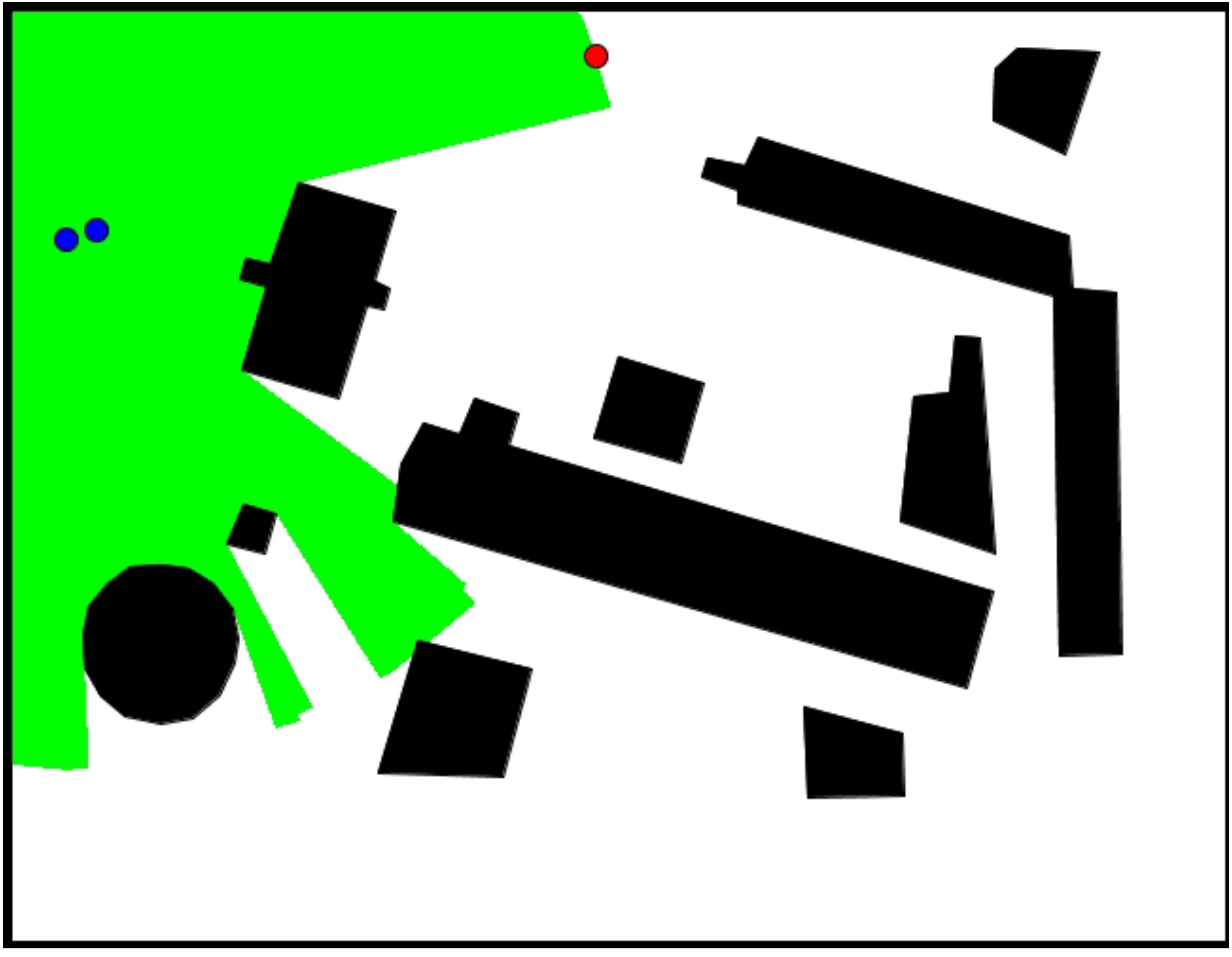
area of *Reachable*$(t \mid O_i)$ – *Viewable*$(t \mid O_i)$, averaged over some time interval

Cooperative Team Behavior

- Trajectories generated using LEL
  - two tracker agents (blue)
  - one target agent (red)



Video



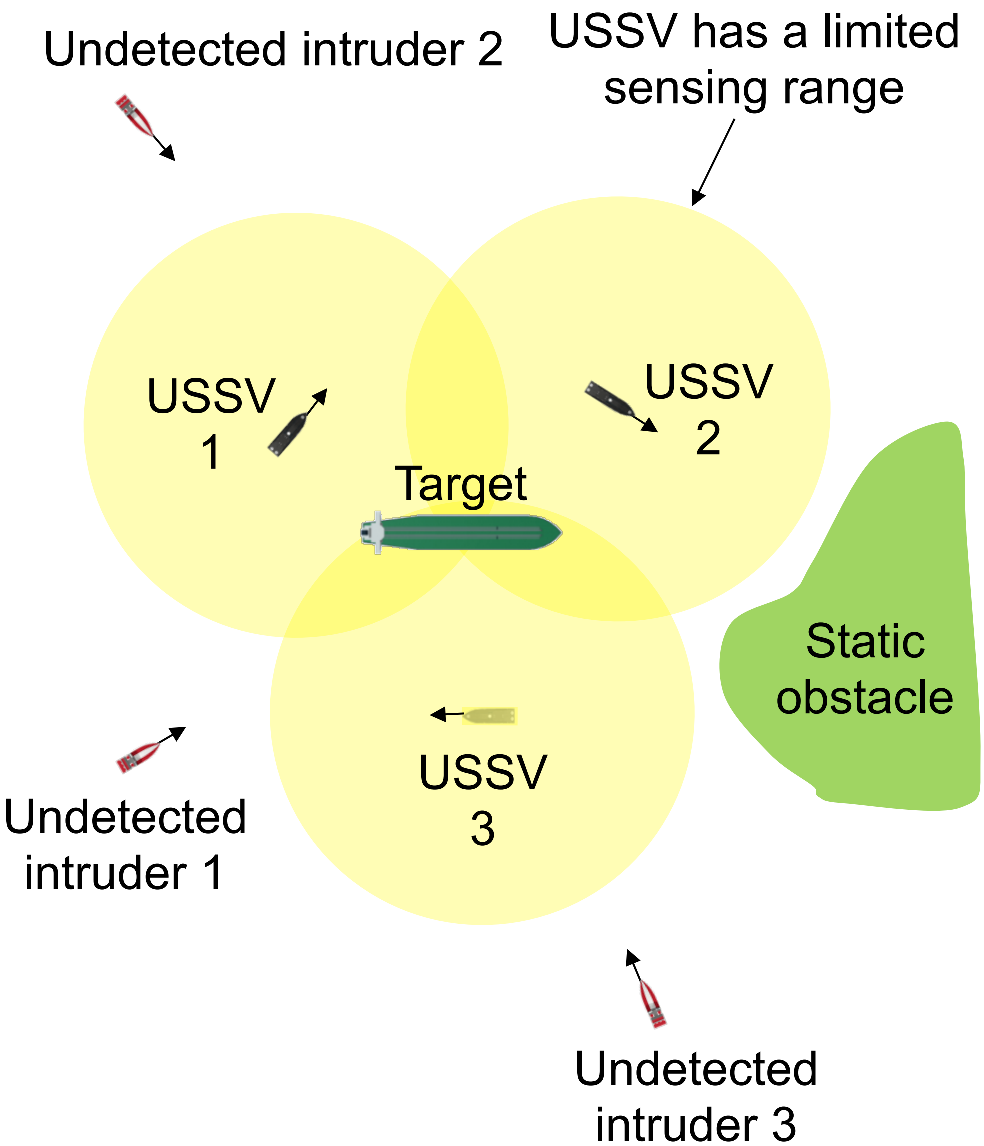
Part 2. Naval Asset Protection

- Generation of behaviors to support multi-USSV blocking and patrolling in the presence of intelligent adversaries

E. Raboin, P. Švec, D. S. Nau, and S. K. Gupta. Model-predictive target defense by team of unmanned surface vehicles operating in uncertain environments. In *IEEE International Conference on Robotics and Automation (ICRA)*, 2013. pdf.

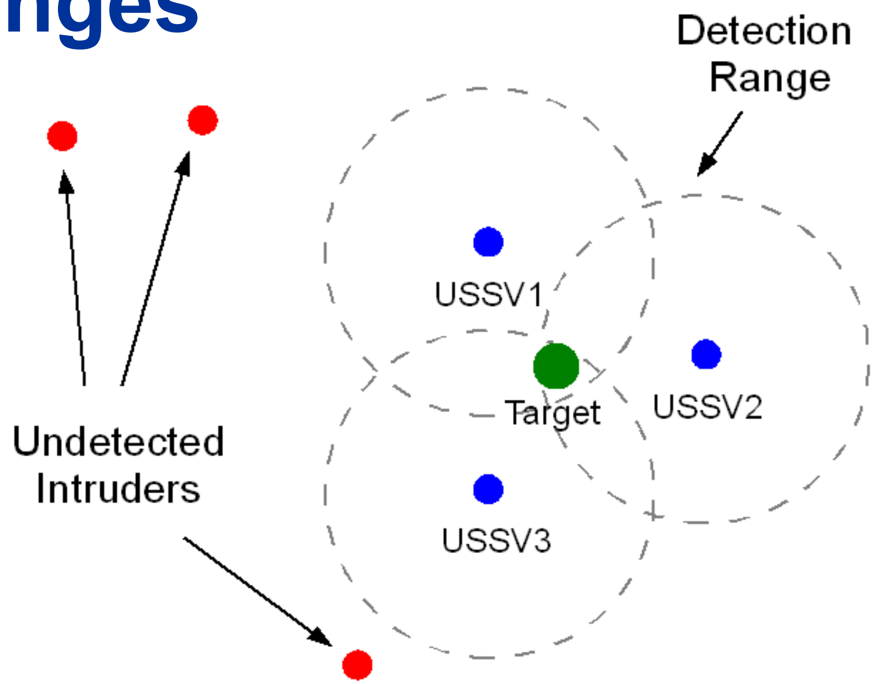
Motivation and Goals

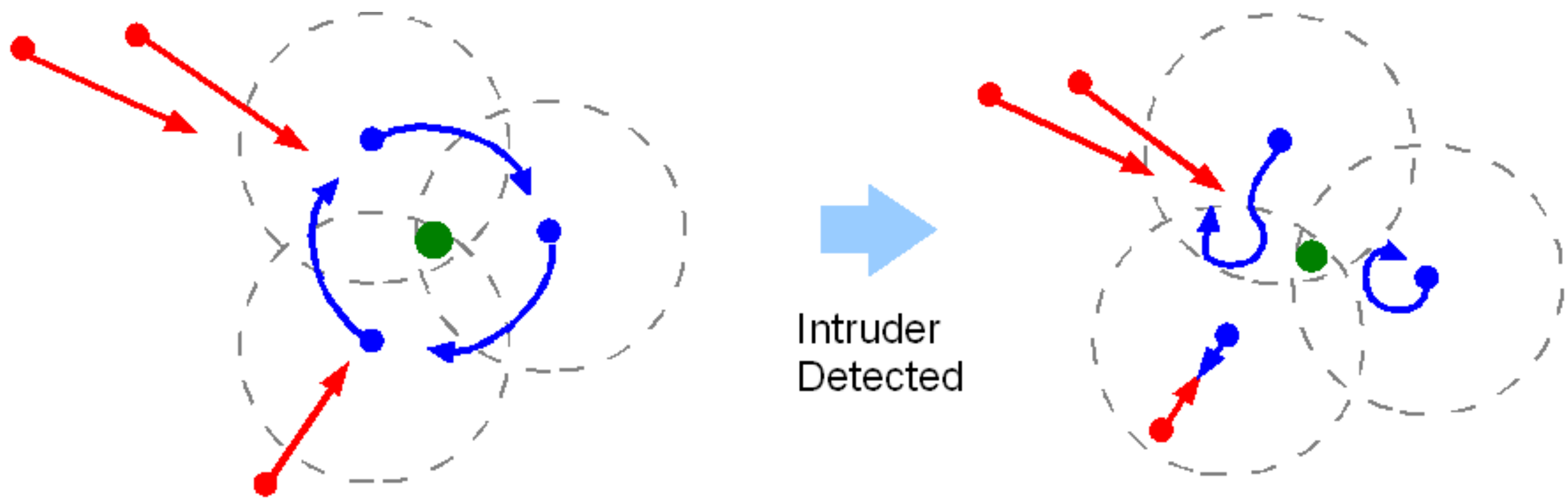
- Group of semi-autonomous USSVs required to patrol an area around an asset to protect it against intruder boats
  - USSVs can have different physical properties
- Goals:
  - Generate multi-USSV, decentralized, and adaptable behavior for patrolling and blocking multiple intruders



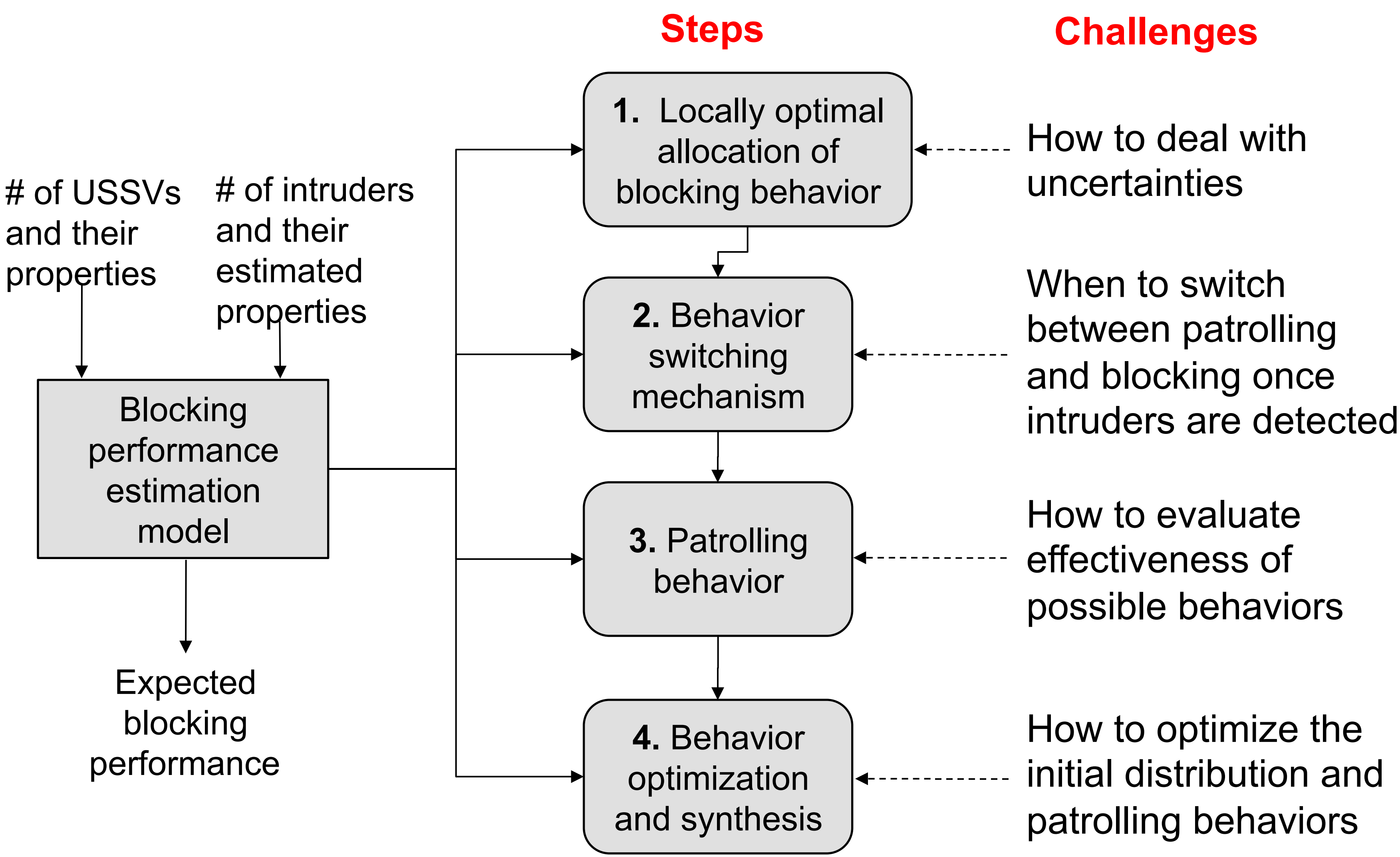
Challenges

- Initial distribution and patrolling behaviors of USSVs
- Patrolling behavior adaptation
  - When to switch between patrolling and blocking behaviors once intruders are detected
  - How to allocate blocking behaviors among USSVs

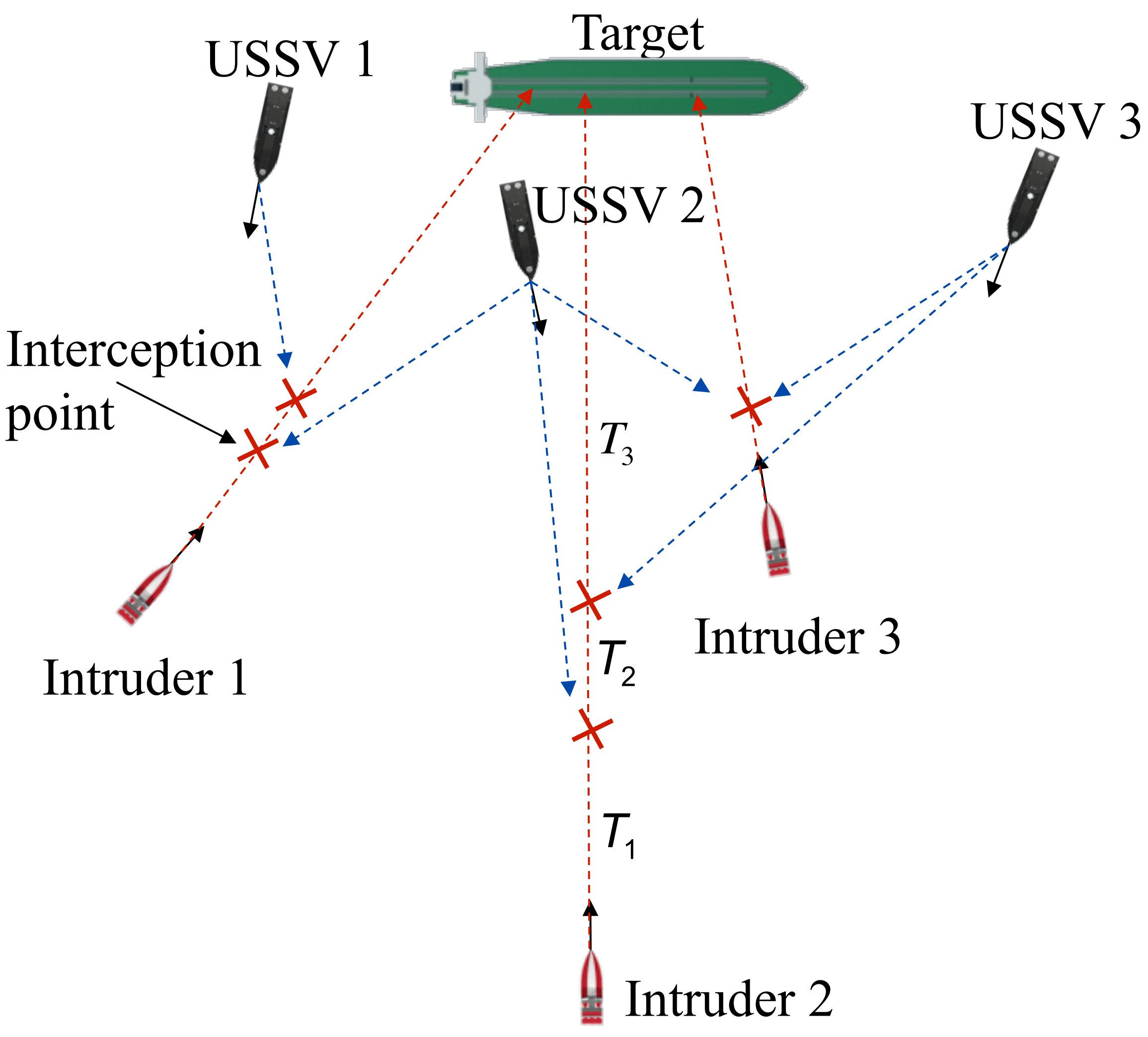




Overall Approach

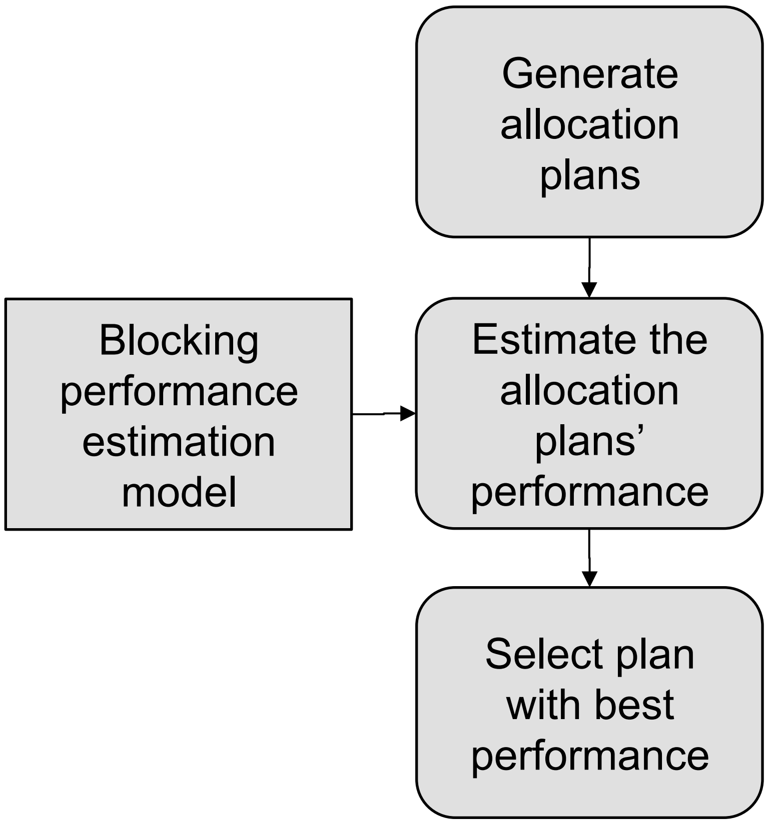


(1) Locally Optimal Blocking Behavior Allocation



(1) Locally Optimal Blocking Behavior Allocation

- Decentralized allocation of blocking behaviors
  - Search for locally best-performing assignment
  - Use knowledge about the defenders' blocking capabilities



$P_1 = (U_1 - I_1, U_2 - I_2, U_3 - I_3)$ **Arr. time 1**

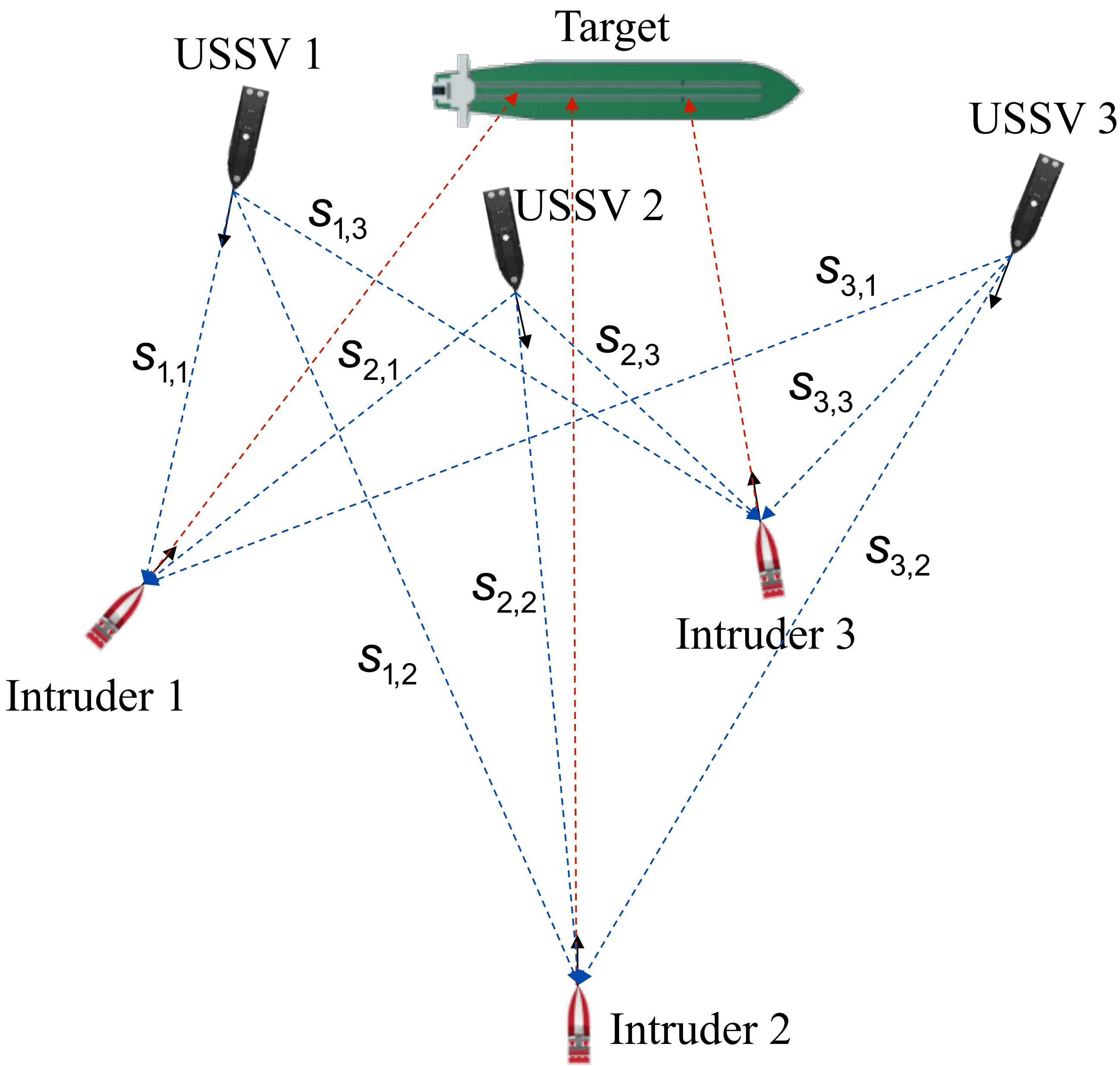
$P_2 = (U_1 - I_1, U_2 - I_3, U_3 - I_2)$ **Arr. time 2**

$P_3 = (U_1 - I_2, U_2 - I_2, U_3 - I_3)$ **Arr. time 3**

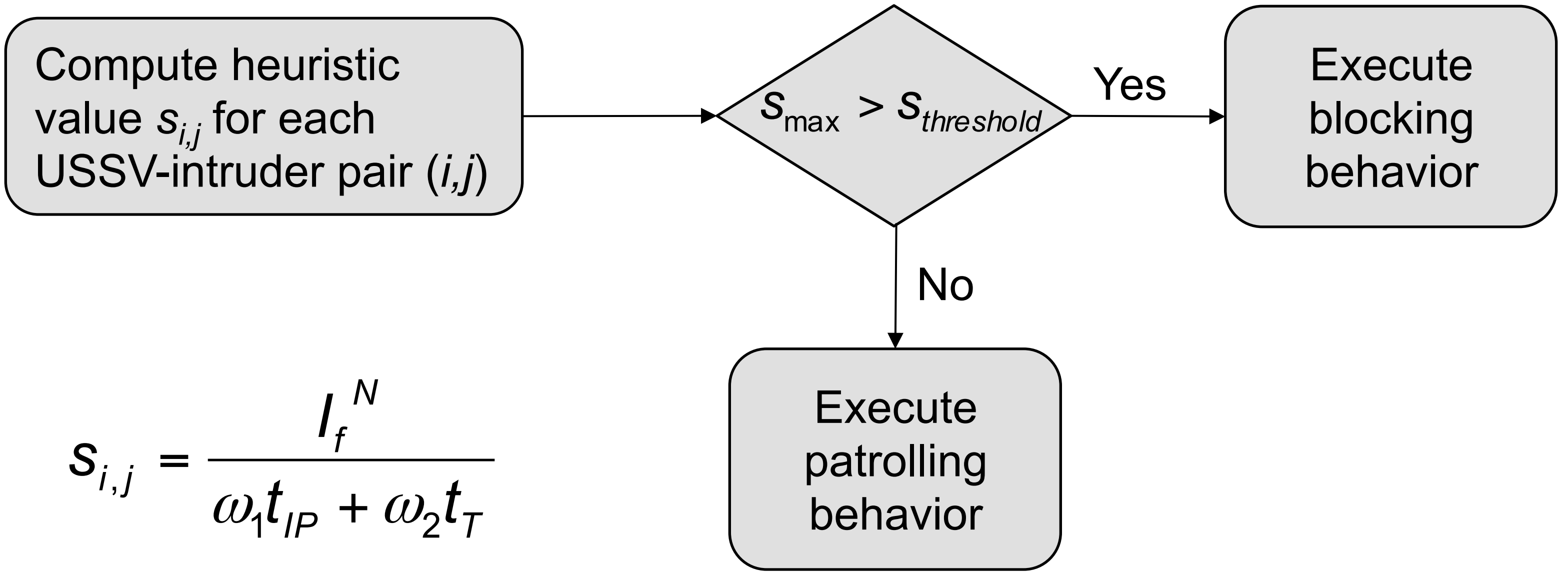
$\dots$

$P_1 = (U_1 - I_1, U_2 - I_2, U_3 - I_3)$

(2) Behavior Switching Mechanism



(2) Behavior Switching Mechanism



$$s_{i,j} = \frac{I_f^{\,N}}{\omega_1 t_{IP} + \omega_2 t_T}$$

I_f – Intruder supress value parameter

N – Number of USSVs following / blocking the intruder j

t_{IP} – Arrival time to the intersection point of the intruder j

t_T – Arrival time to the target

ω_1, ω_2 – Weight parameters

(3) Patrolling Behavior

The quality of a patrol route can be evaluated given a set of hypothetical intruders. For each intruder *i*, compute:

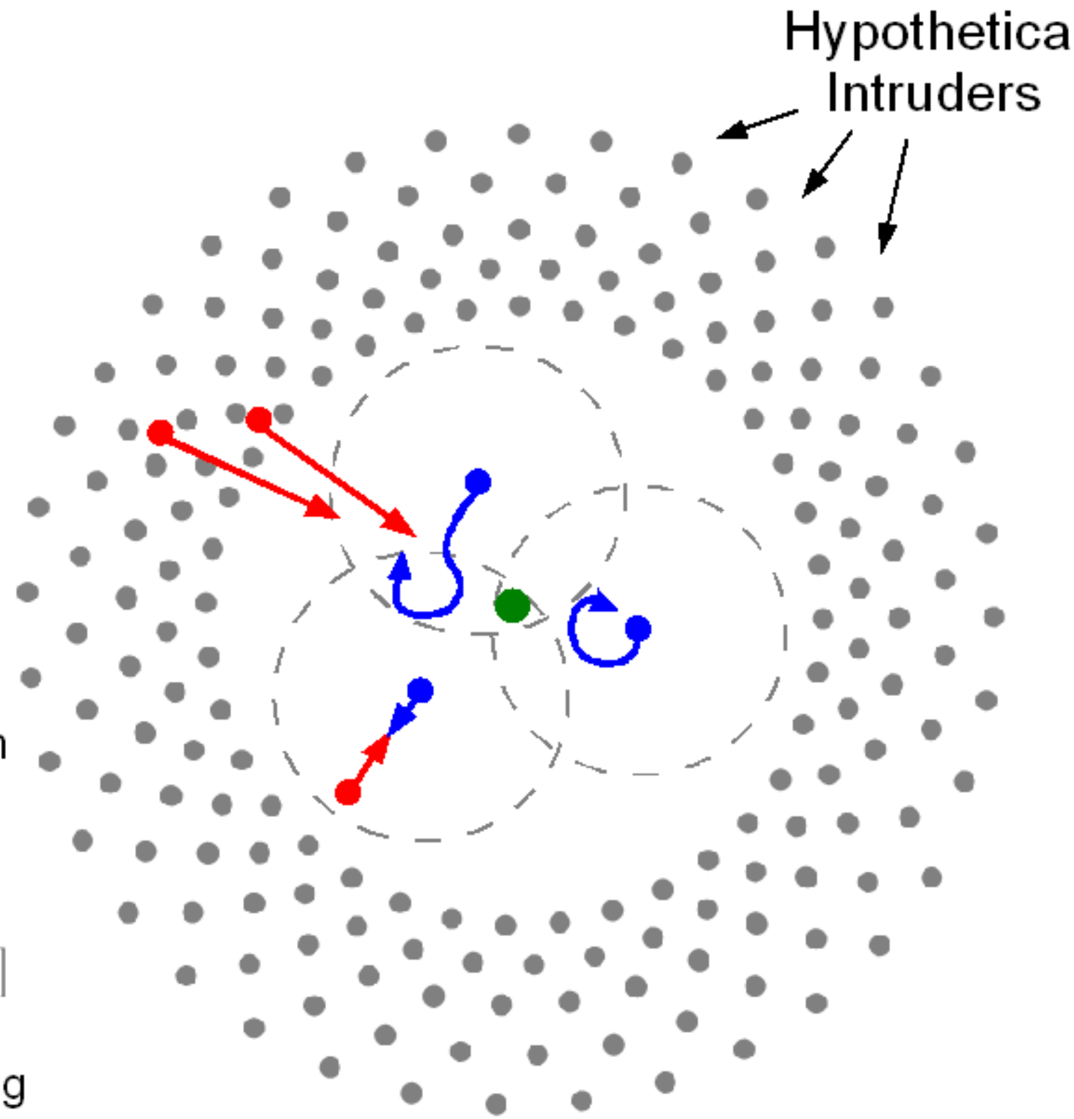
$P_i(t_d | r_j)$: probability that intruder *i* will be detected at time t_d by a USSV following route r_j

$t_i(t_d, r_j)$: time when intruder *i* will collide with the target if detected a time t_d and immediately intercepted by a USSV following route r_j

Given set of routes, $r_1, r_2, \ldots r_n$ for a team of *n* USSVs, we estimate the expected collision time using the formula:

$$\frac{1}{mk} \Sigma_{i=1}^{m} \Sigma_{t=t_0}^{t_k} max_j [P_i(t|r_j) t_i(t, r_j)]$$

This can be computed efficiently, allowing for thousands of candidate routes to be evaluated in under a second.

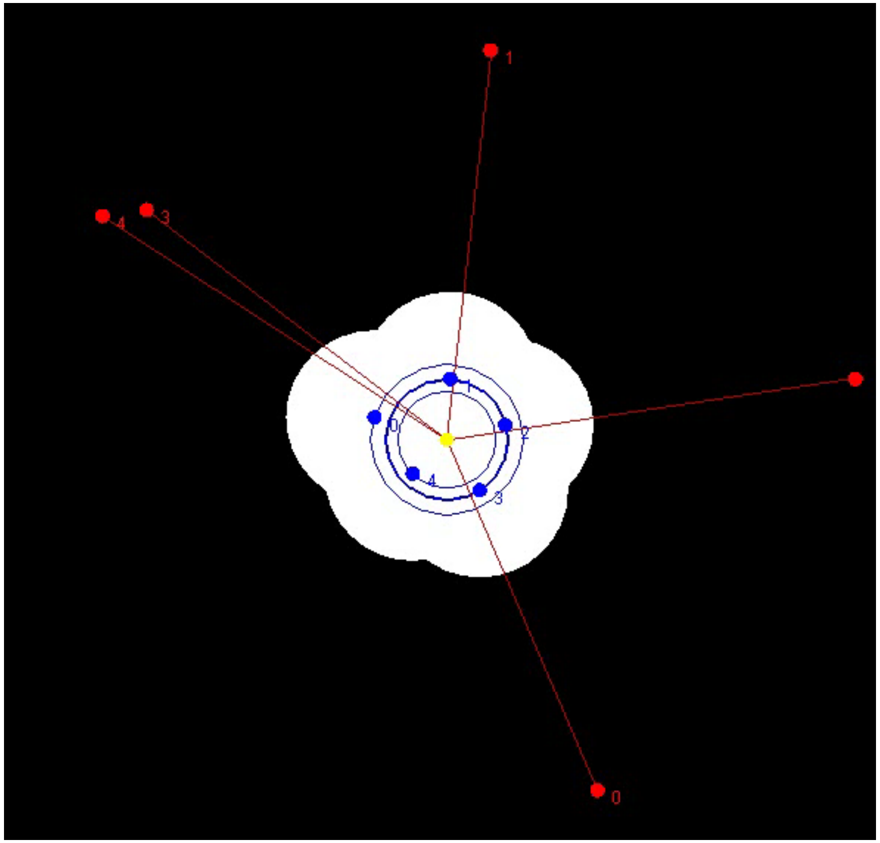


(4) Policy Optimization

- Genetic Algorithm (GA) to optimize:
  - (d_i, ϕ_i) – Initial locations of USSVs around the target
  - $s_{threshold}$ – Heuristic value threshold
  - I_f – Intruder suppress value parameter
  - ω_1, ω_2 – Shame equation weight parameters

- Several different types of defending policies
  - Baseline
  - Motivation-based
  - Purely patrolling
  - Hybrid (combination of Motivation-based & Patrolling)

Multi-USSV Patrolling Behaviors: Results



Simple defender policy

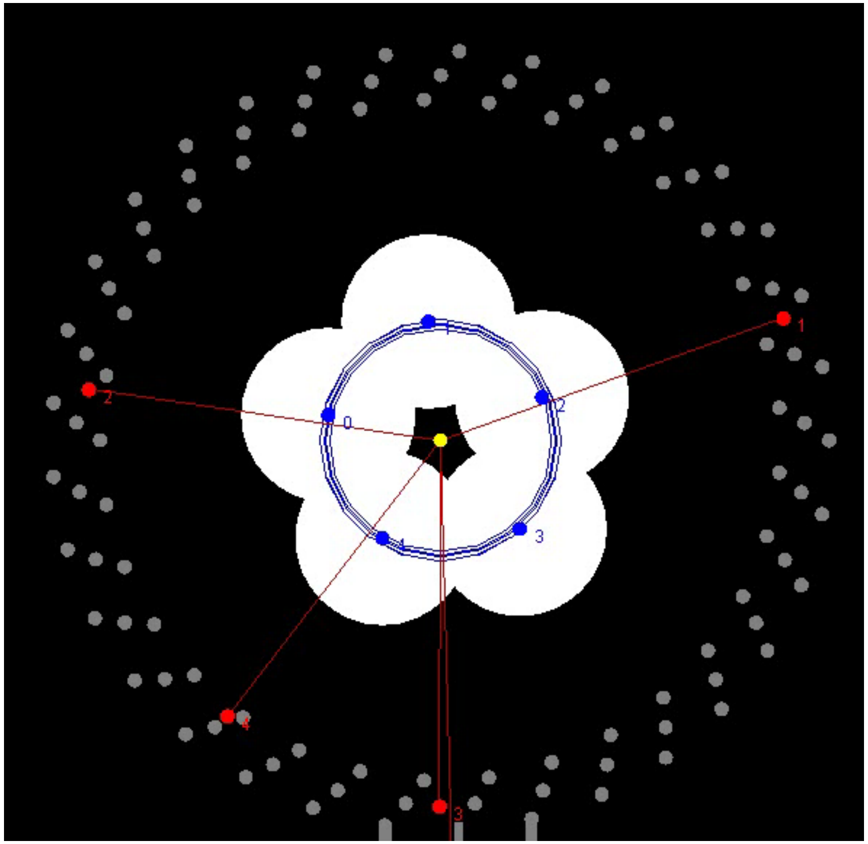
Max. velocity of USSVs: 10 m/s

Max. velocity of intruders: 9 m/s

Visibility radius of vehicles: 60 m

Range of initial distances of intruders from the target: 250-300 m

Average optimized initial distance of USSVs from the target: 42 m



Purely patrolling defender policy

Max. velocity of USSVs: 10 m/s

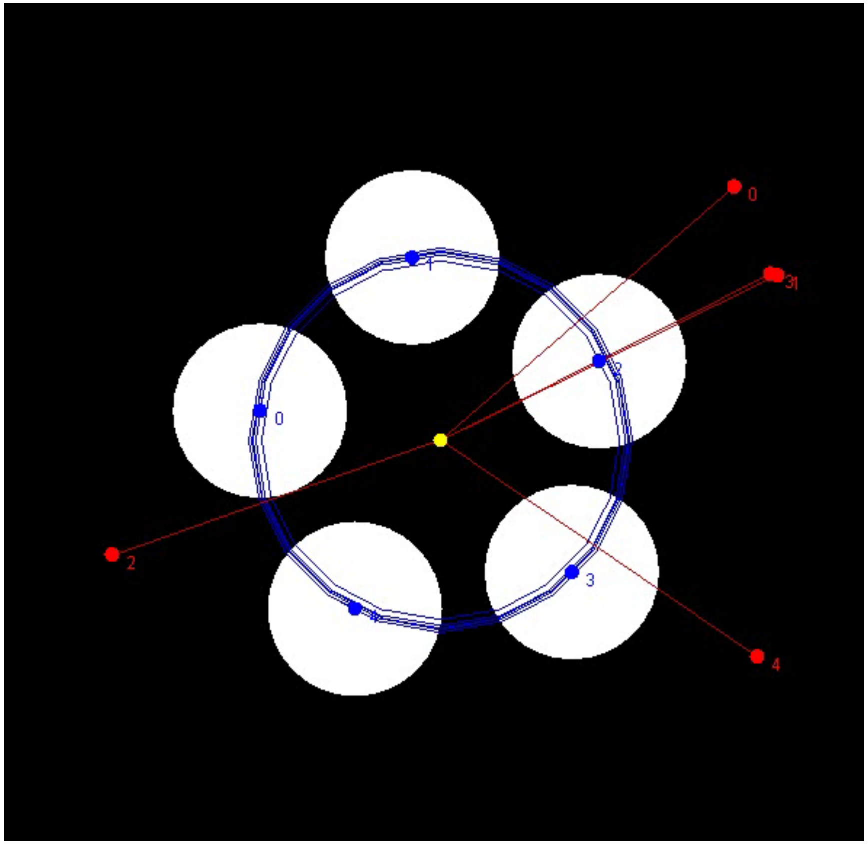
Max. velocity of intruders: 9 m/s

Visibility radius of vehicles: 60 m

Range of initial distances of intruders from the target: 250-300 m

Average optimized initial distance of USSVs from the target: 80 m

Multi-USSV Patrolling Behaviors: Results (continued)



Motivation based defender policy

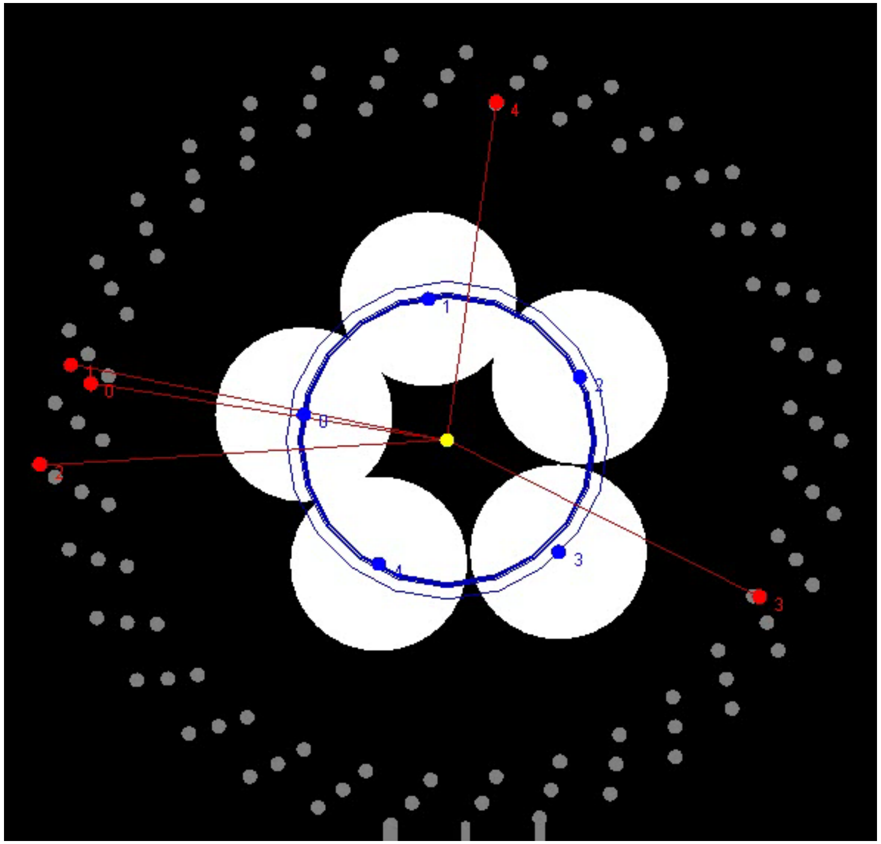
Max. velocity of USSVs: 10 m/s

Max. velocity of intruders: 9 m/s

Visibility radius of vehicles: 60 m

Range of initial distances of intruders from the target: 250-300 m

Average optimized initial distance of USSVs from the target: 128 m



Hybrid defender policy

Max. velocity of USSVs: 10 m/s

Max. velocity of intruders: 9 m/s

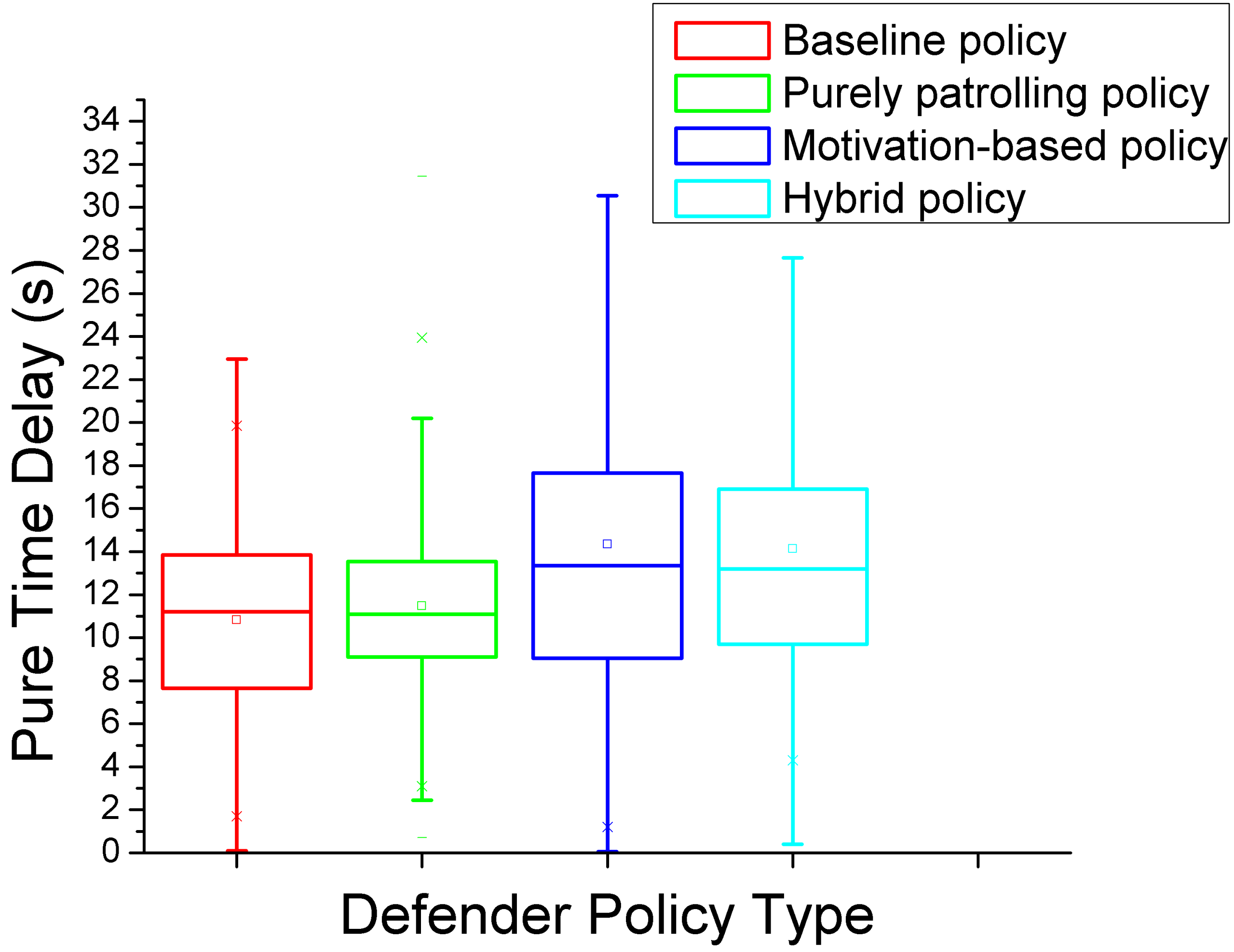
Visibility radius of vehicles: 60 m

Range of initial distances of intruders from the target: 250-300 m

Average optimized initial distance of USSVs from the target: 101 m

Multi-USSV Patrolling Behaviors: Results (continued)

- Policies evaluated using 10000 simulation runs



Summary

- Formalisms and algorithms for multi-agent tracking-and-evasion
    - Temporarily sacrificing visibility can provide a strategic advantage
  - » Gridworld, full communication among trackers
    - ***RLA*** heuristic, imperfect-info game-tree search
  - » Continuous Euclidean space, limited communication among trackers
    - ***LEL*** (Limited-Communication Euclidean Lookahead) heuristic

- Generation of behaviors for multi-USSV blocking and patrolling in the presence of intelligent adversaries
  - » Adaptation of patrolling behavior
  - » When to switch between patrolling and blocking behaviors once intruder is detected
  - » Allocation of blocking behaviors