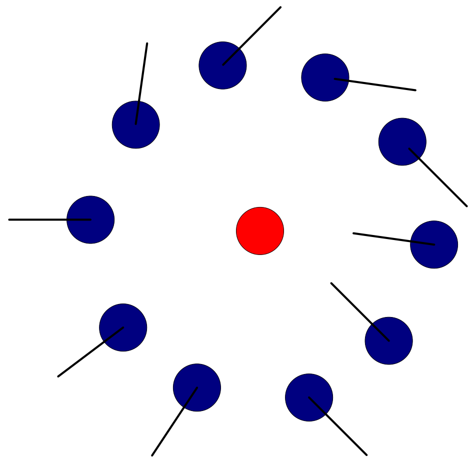
Multi-threat Containment with Cooperative Autonomous Agents



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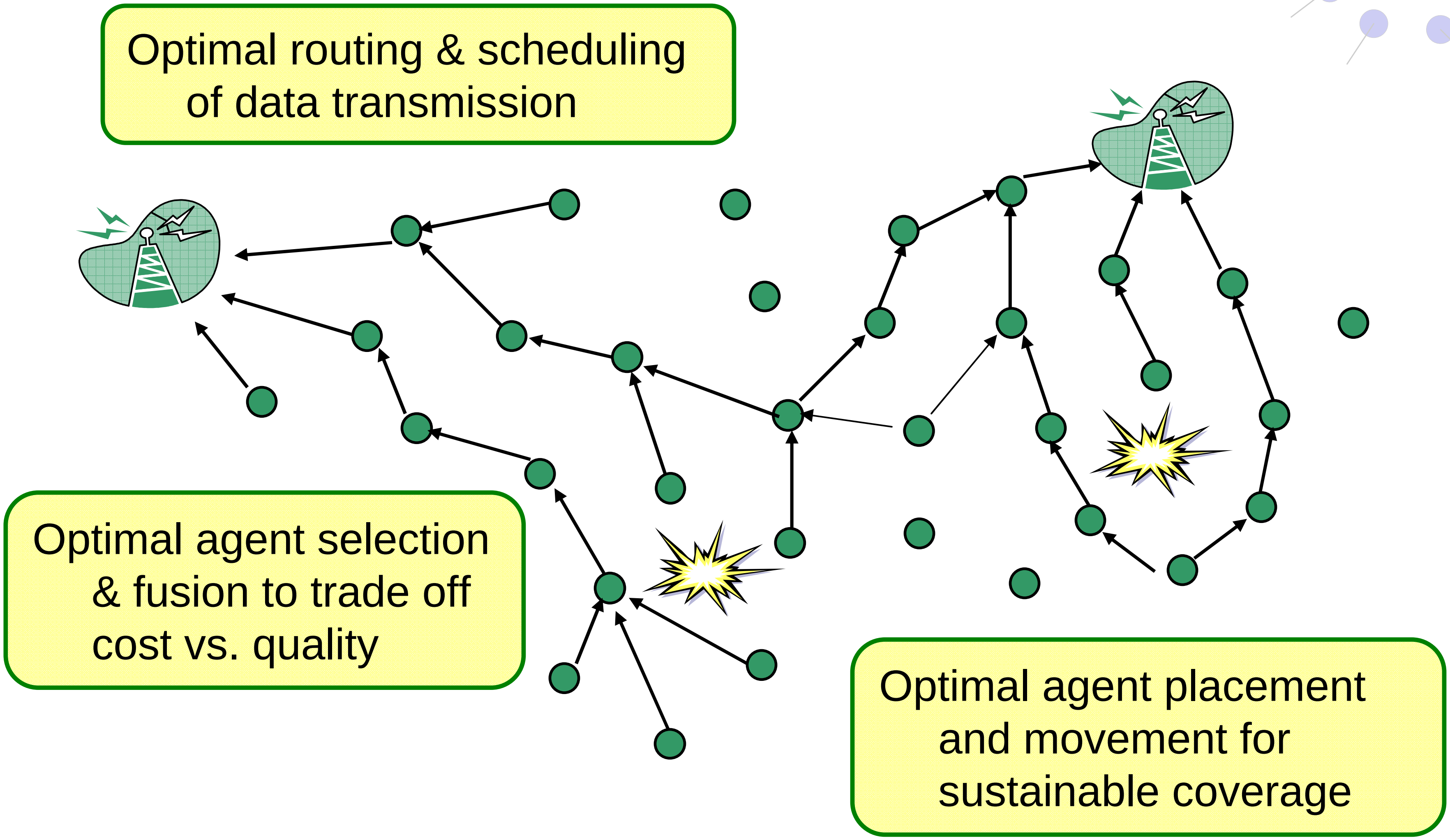
Collaborative sensing & fusion



Optimal routing and scheduling

Q: How to jointly optimize the path and the time to transmit?

$$\max \quad \sum_{i \in S} \sum_{j \in N_t(i)} \sum_{k=1}^{K} F_{jik} c_{ji}$$

subject to

$$T_k - M(1 - X_{ijk}) \;\leq\; F_{ijk} \;\leq\; \min(T_k, M \cdot X_{ijk}) \quad \forall i \in N,\ j \in N \cup S,\ 1 \leq k \leq K \qquad (1)$$

$$T_k - M(1 - Y_{ik}) \;\leq\; G_{ik} \;\leq\; \min(T_k, M \cdot Y_{ik}) \quad \forall i \in N,\ j \in N \cup S,\ 1 \leq k \leq K \qquad (2)$$

$$\sum_{j \in N_r(i)} \sum_{l \in N_t(j)-i} X_{ljk} - M(1 - \sum_{j \in N_r(i)} X_{ijk}) \;\leq\; 0 \quad \forall i \in N,\ 1 \leq k \leq K \qquad (3a)$$

$$\sum_{j \in N_t(i)} \sum_{l \in N_r(j)-i} X_{jlk} - M(1 - \sum_{j \in N_t(i)} X_{jik}) \;\leq\; 0 \quad \forall i \in N,\ 1 \leq k \leq K \qquad (3b)$$

$$Y_{ik} - (\sum_{j \in N_r(i)} X_{ijk} + \sum_{j \in N_t(i)} X_{jik}) \;\geq\; 0 \quad \forall i \in N,\ 1 \leq k \leq K \qquad (4a)$$

$$Z_{ik} - (\sum_{j \in N_r(i)} X_{ijk} - \sum_{j \in N_r(i)} X_{ijk-1}) \;\geq\; 0 \quad \forall i \in N,\ 2 \leq k \leq K \qquad (4b)$$

$$W_{ik} - (Y_{ik} - Y_{ik-1}) \;\geq\; 0 \quad \forall i \in N,\ 2 \leq k \leq K \qquad (4c)$$

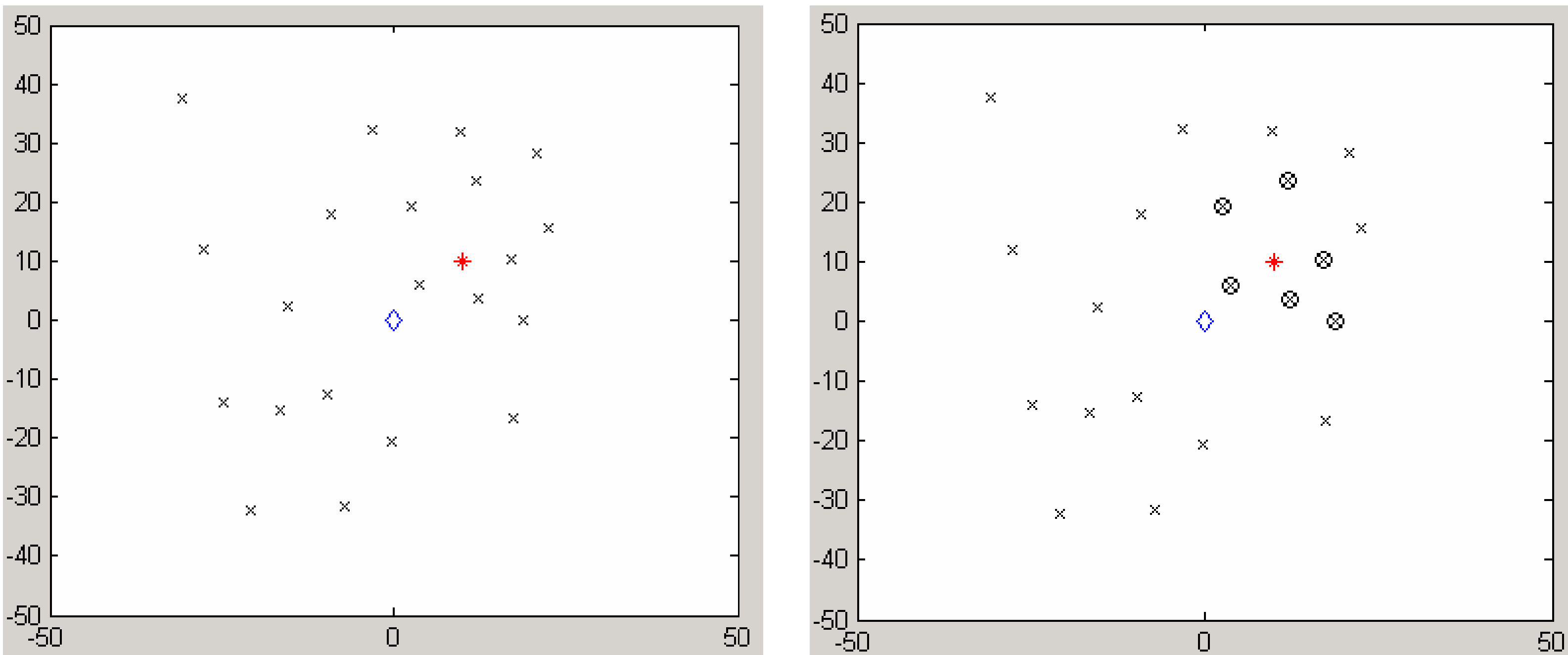
$$0 \;\leq\; \sum_{l=1}^{k} \sum_{j \in N_t(i)} c_{ji} F_{jil} + \sum_{l=1}^{k} \lambda_{il} T_l - \sum_{l=1}^{k} \sum_{j \in N_r(i)} c_{ij} F_{ijl} \;\leq\; b_i \quad \forall i \in N,\ 1 \leq k \leq K \qquad (5)$$

$$e_i^{sr} \sum_{k=1}^{K} W_{ik} + e_i^{rt} \sum_{k=1}^{K} Z_{ik} + p_i^{s} \sum_{k=1}^{K} T_k + p_i^{r} \sum_{k=1}^{K} G_{ik} + p_i^{t} \sum_{k=1}^{K} \sum_{j \in N_r(i)} F_{ijk} \;\leq\; e_i^{tot} \quad \forall i \in N \qquad (6)$$

A: Identify sensor roles and find relaxation of problem

Optimal joint estimation and delivery

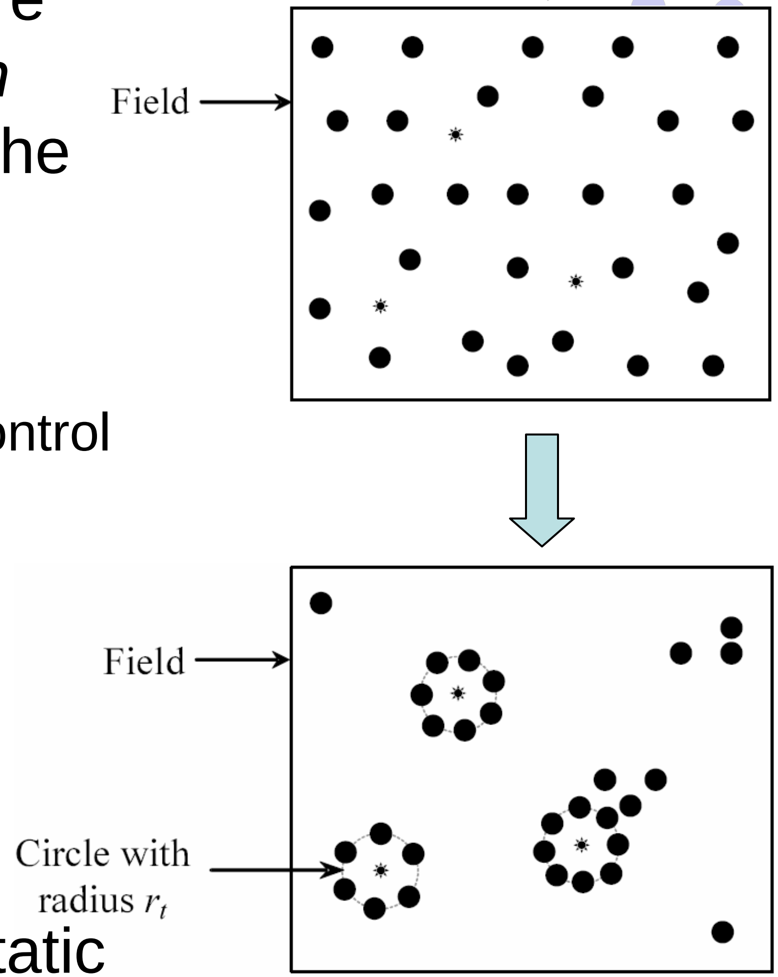
Q: How are the cost and accuracy affected by the selection of sensing nodes in a collaborative sensing network?



A: numerical analysis with Networked Slepian-Wolf Coding assuming Gaussian random observations.

Multithreat Containment

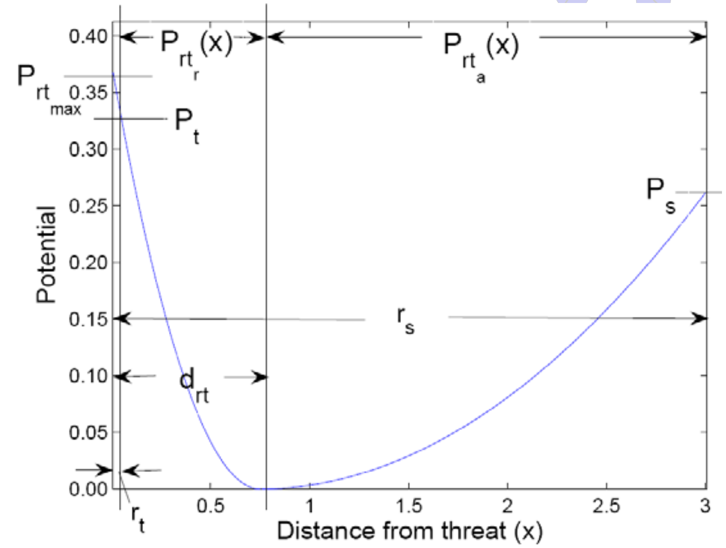
- Given a 2D field of interests, where threats appear at random times, *n* robots need to contain (encircle) the threats within a time interval *t*.
- Robot-Capabilities:
  - No communication, no centralized control
  - Local sensing, limited range
- Challenges:
  - Collision avoidance
  - Moving toward specific threat
  - Evenly spread around the threat
- Existing work focuses on single static threat



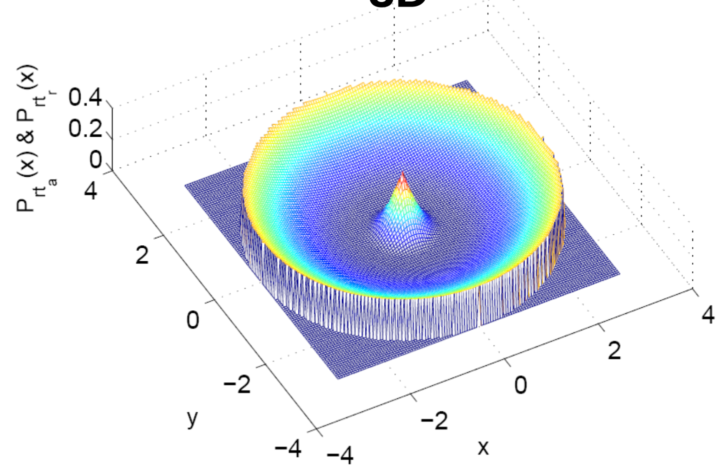
MUTCA = QAPFs + Random Walk

- Artificial Potential Function (APF)
  - Mathematical functions that mimic gravitational potential, wherein robots as Newtonian particles $\vec{F} = -\Delta\vec{P}$
- Quadratic APF (QAPF)
  - Simple yet does the job
- Three QAPFs
  - Moving toward the threats
  - Collision avoidance
  - Evenly spread around the threats
- Threats come and go
  - Robots need to be able to re-distribute over the field to provide continuous coverage
  - **Random walk** while not detecting forces

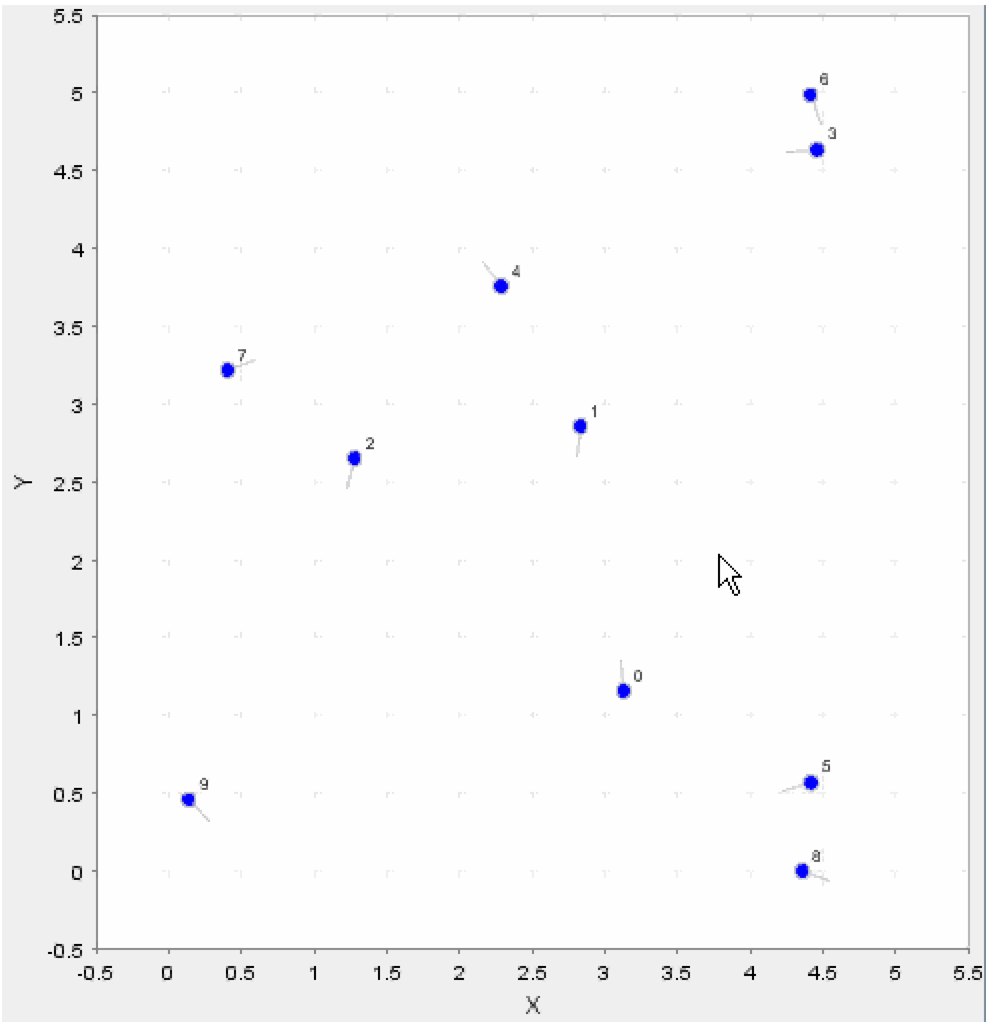
2D



3D



Sample video



- 10 Robots randomly moving until a threat occurs …

Simulation parameters

Parameter	Default Value
Environment dimensions	10m×10m
Simulation time	7200s
Maximum tolerance to calculate success of robots	$1.25r_{max}$
Threat Radius (r_t)	0.05m
Arrival Rate (λ)	0.01/s
Constant lifetime of threat ($\frac{1}{\mu}$)	60s
Number of robots	50
Seed for random number generators	time since UNIX® epoch at runtime

Algorithm Parameters

Parameter	Default Value
Radius	0.05m
Maximum angular velocity	π/s
Maximum velocity	0.1m/s
Battery voltage	9V
Battery capacity	3000mAh
Single motor current consumption	0.25A
Ideal sensor current consumption	0.005mA/sense
Mass of robot (m)	1kg
Sensing Range (r_s)	3m

Physical Parameters

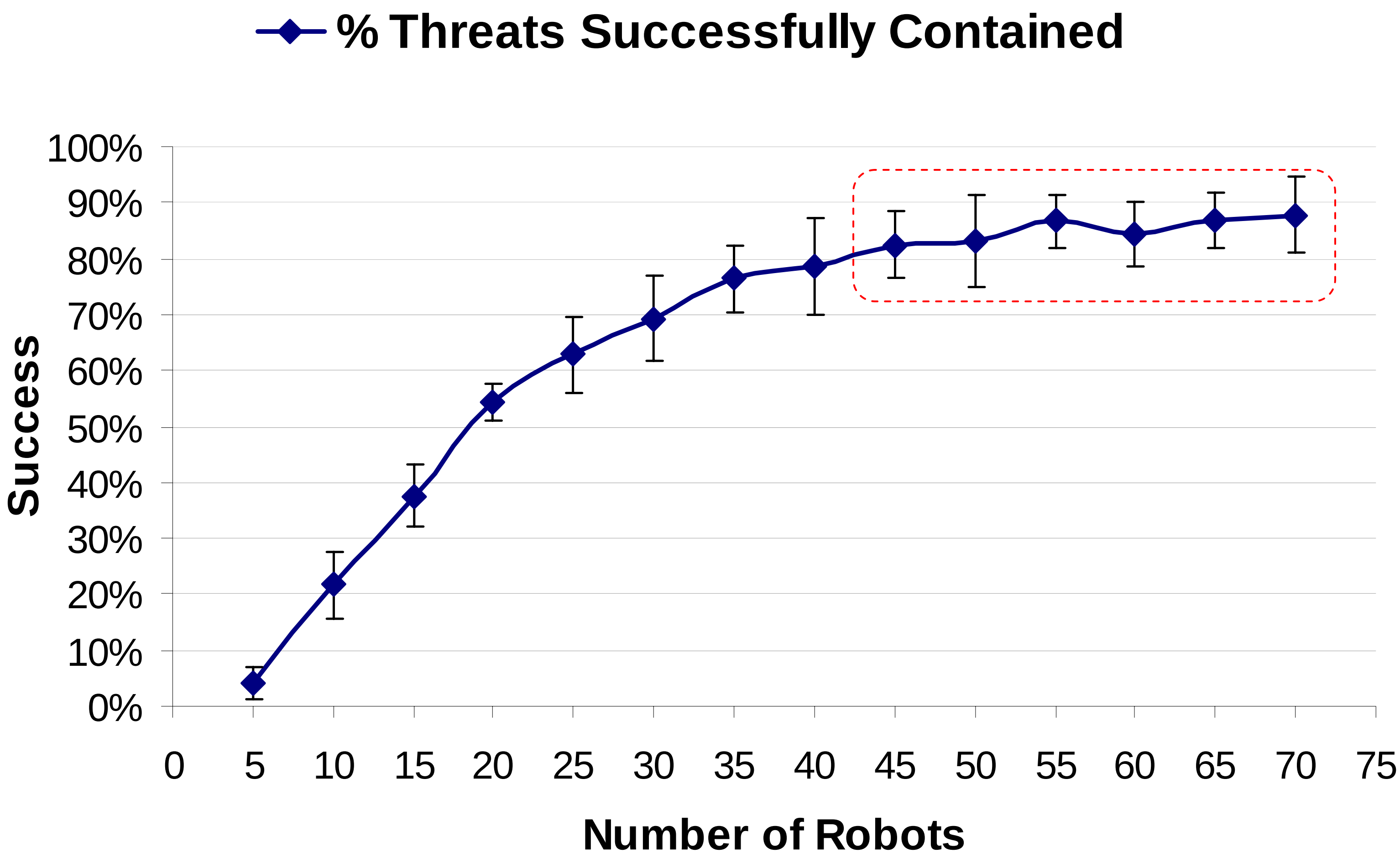
Choice of Parameters:

- Through experimentation.
- Based on common applications.

Parameter	Default Value
Closest robots can ever get (ϵ)	0.02m
Percentage difference between $P_t(x)$ and $P_s(x)$ (p)	20%
Formation Radius (d_{rt})	0.75m
Range of robot repulsion (distance within which the robots experience repulsion, d_{rep})	0.3m
Safe distance on robot repulsion (ideal distance between two robots, $d_{r_{rep}}$)	1m
Friction factor (f)	15%
Spreading distance (increased sensing distance used by robots to calculate spreading forces. See Figure 2.10)	1.6m
Ideal spreading distance (ideal distance between two robots when calculating spreading forces)	2.5m
Number of robots to detect before going into Spreading mode (n)	2
Range in which robot decides to calculate spreading forces	$0.8d_{rt}$ to $1.2d_{rt}$
Time for which robots will travel when there is a zero force condition	20s
% error in sensing distance (e_s%) to any robot or threat	0%

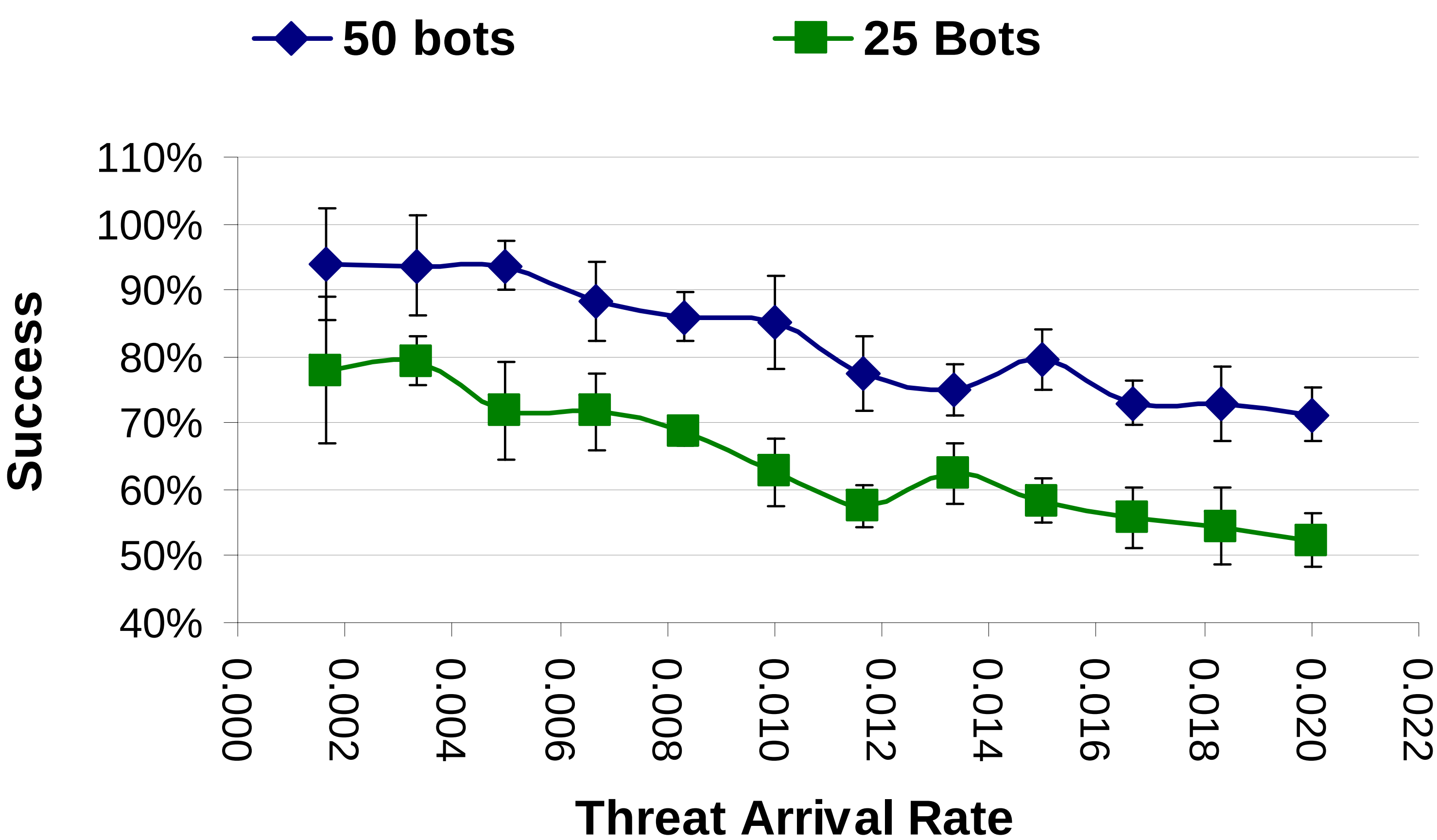
Environmental Parameters

Results: Success vs. # Robots



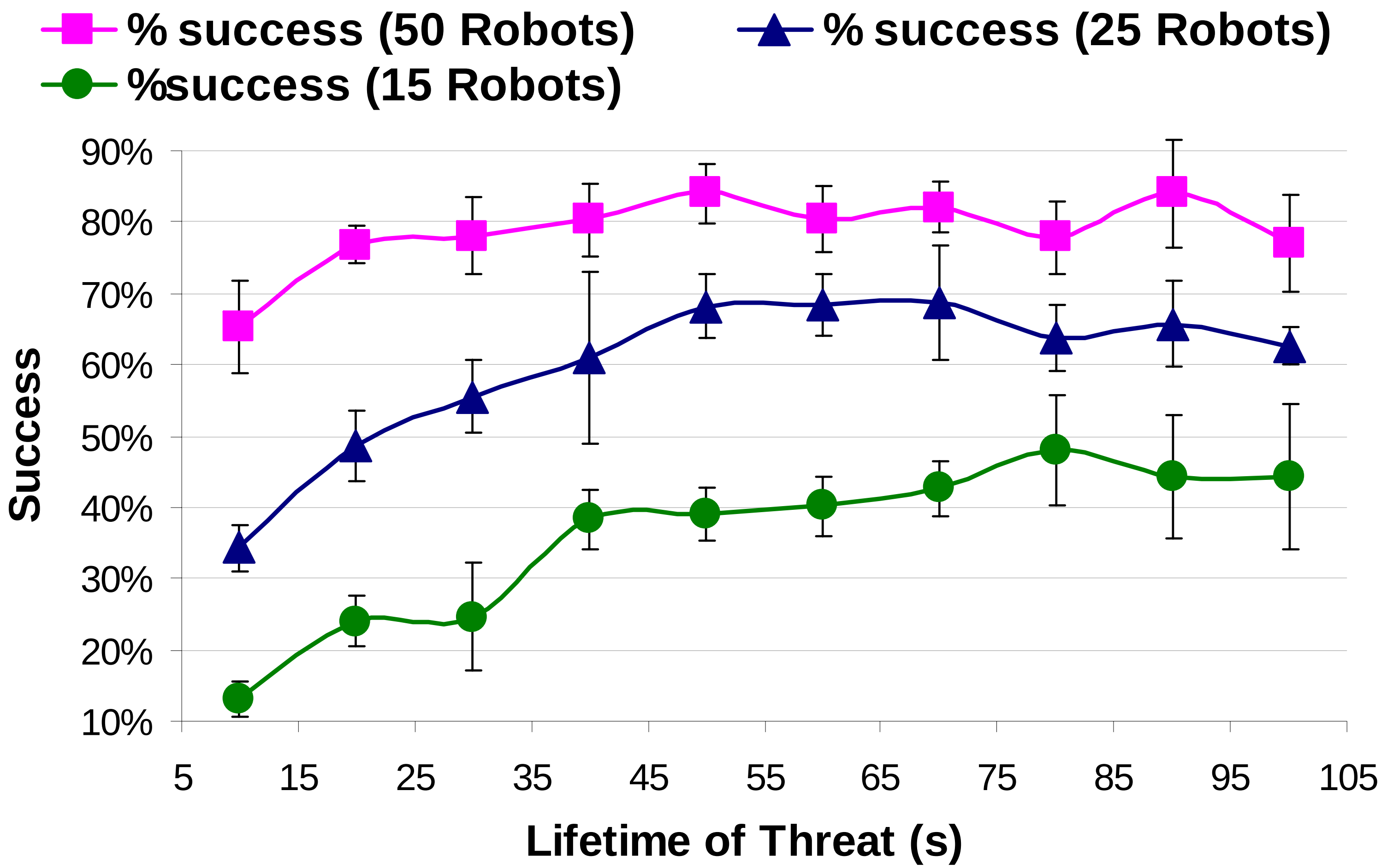
- Cap-off with 50+ robots.
- Excessive robots may also cause unnecessary local potential minima

Results: Success vs. Threat Arrival Rate



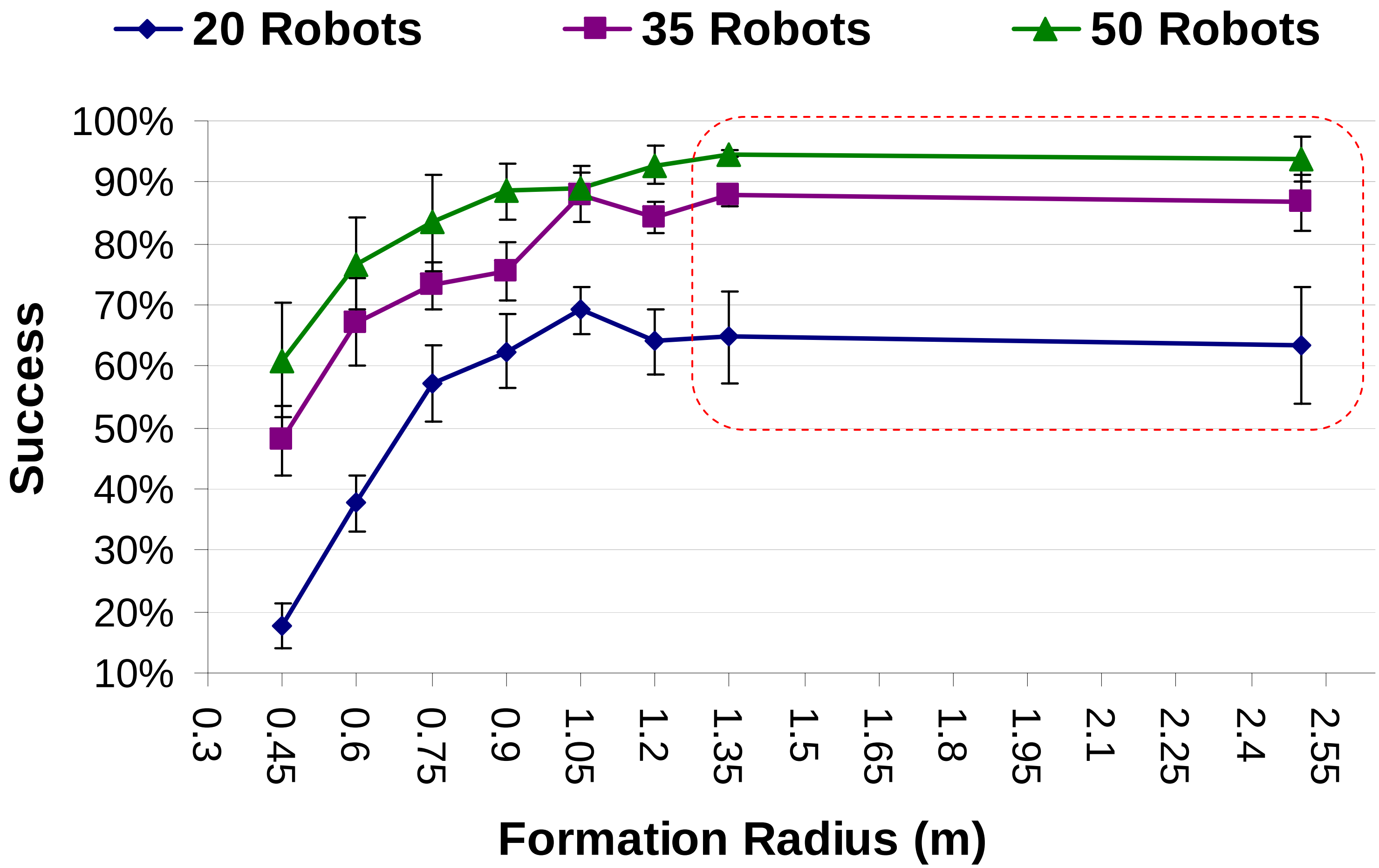
- Higher arrival rates cause higher instability
- Dynamics in the time domain is more critical than spatial dynamics

Results: Success vs. Threat Lifetime



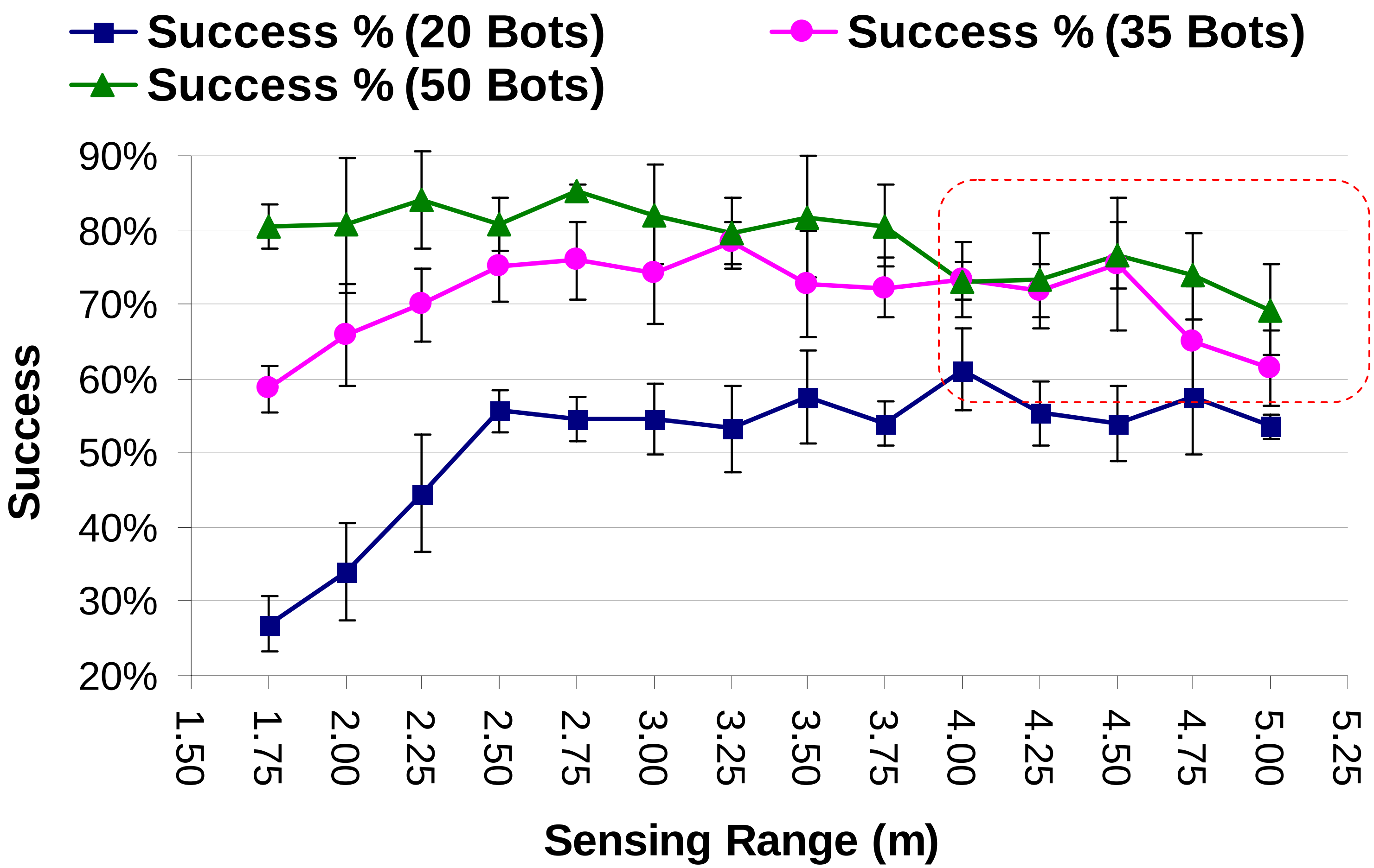
- No higher dynamics with longer lifetime, just more time for containment
- Additional lifetime present no benefit

Results: Success vs. Containment Radius



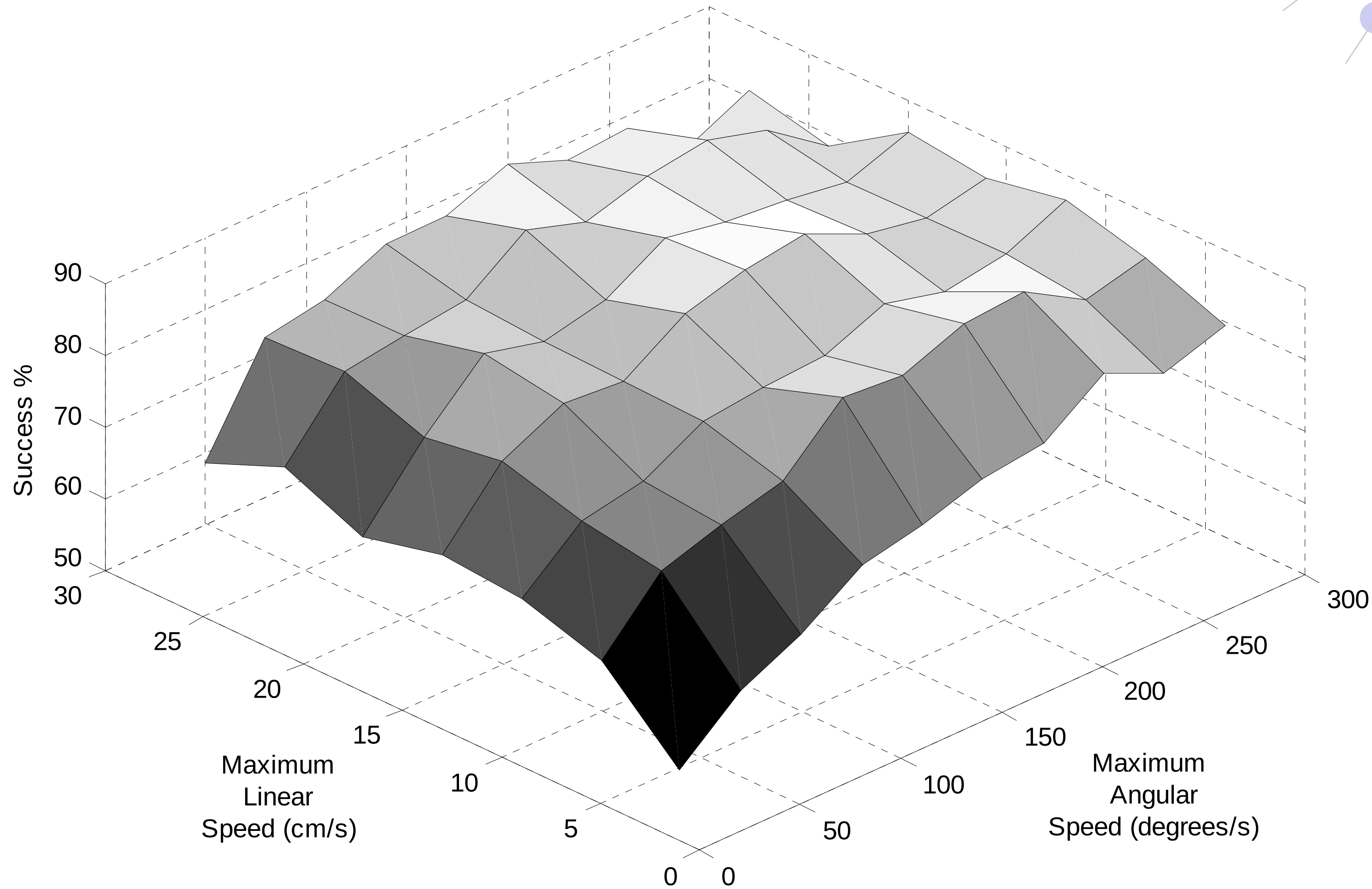
- Larger containment radius makes it easier for robot to move to threat
- Yet, at some point there aren't enough robots sensing the same threat

Results: Success vs. Sensing Range



- Larger sensing range gives a more complete picture of the surroundings
- Yet, sense more robots and threats means excessive forces perceived, casing unstable containment

Results: Success vs. Angular Speed & Linear Speed



- Angular velocity affects success more than locomotion velocity.

Concluding Remarks

- Still many open problems for collaborative sensing and fusion
  - Networking problems
  - Joint estimation and fusion problems
  - Autonomous robot team problems
- MUTCA provides a simple solution for naïve agents
  - Higher sensing and locomotion capability may not be necessary (or even detrimental) for successful containment
- Extensions to deal with moving and spreading threats
  - How to model the dynamics?
  - Swarm optimization or Lyapunov function analysis?
  - Prediction of adversary behavior