ORTA DOĞU TEKNİK ÜNİVERSİTESİ
MIDDLE EAST TECHNICAL UNIVERSITY

DYNAMIC FORMATION CONTROL WITH HETEROGENEOUS MOBILE ROBOTS

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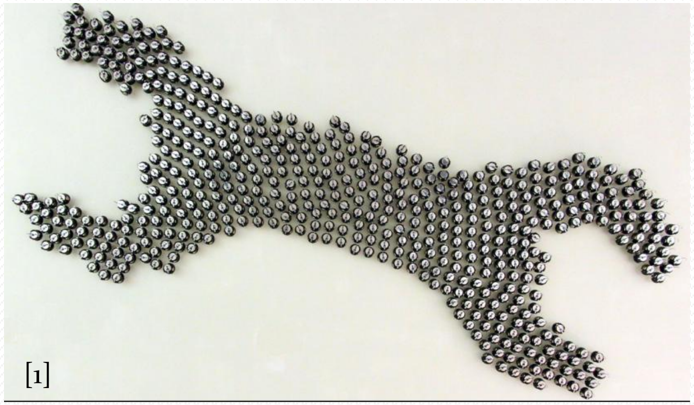
Ankara

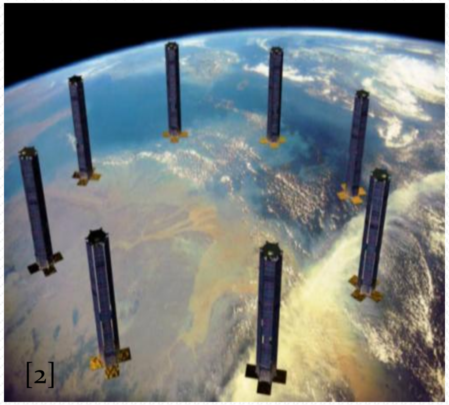
Outline

- Introduction
- Motivation
- System Overview
- Local Positioning System Design
- Formation Control System Design
- Results
- Conclusion and Future Works
- References

Introduction

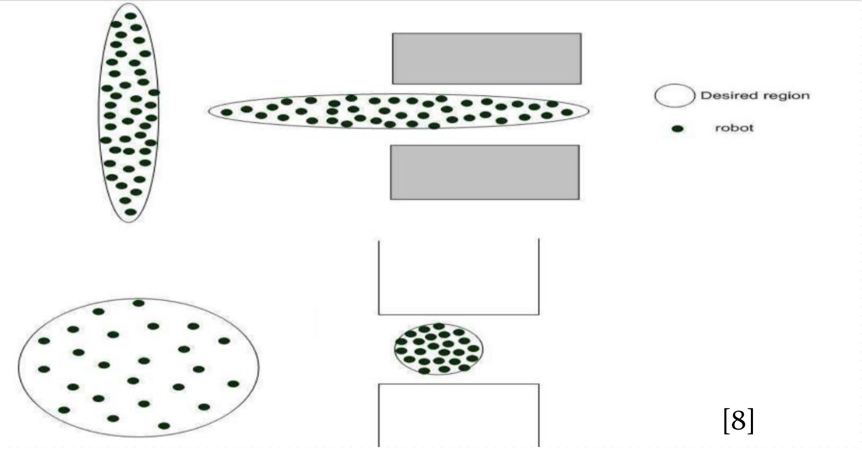
This thesis work focuses on dynamic adaptation to achieve changes in formation of swarms consisting of heterogenous mobile robots





Motivation - 1

Formation control solutions are generally implemented with simple geometrical shapes which don't change with time.



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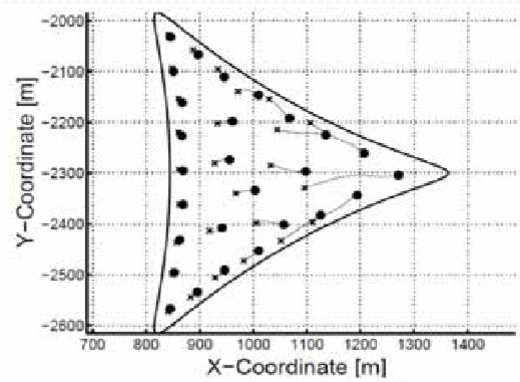

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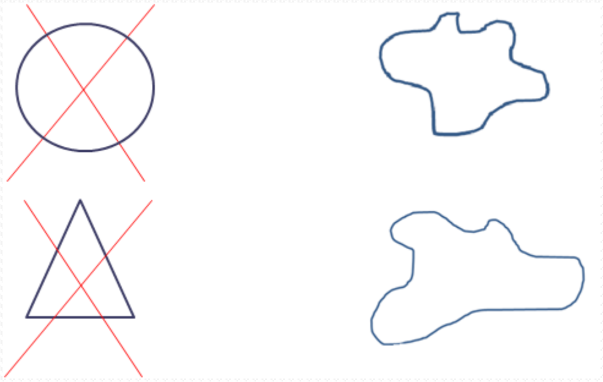
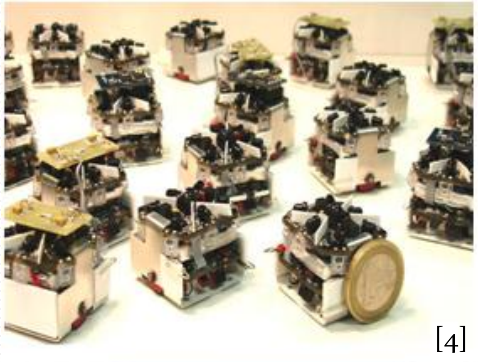
Our aim

- Designing a formation control system for **complex** and **dynamically changing** shapes



Motivation - 2

The research about the formation control, mainly focuses on swarms with homogenous agents.

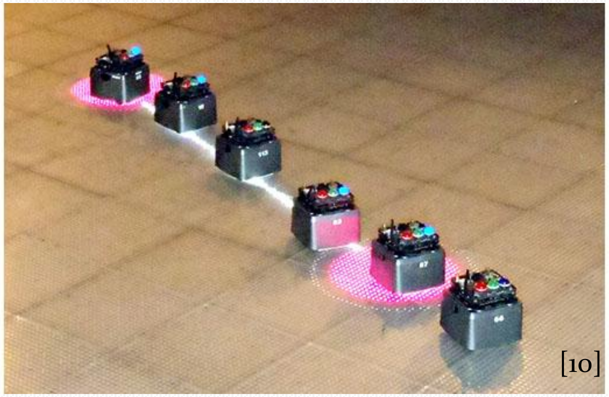


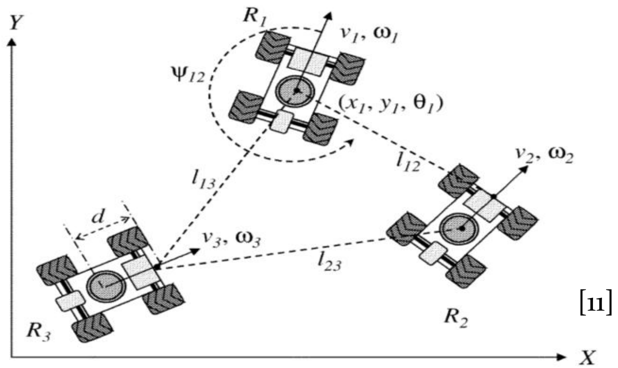
Our aim

- Designing a formation control system with **heterogeneous** agents

Motivation - 3

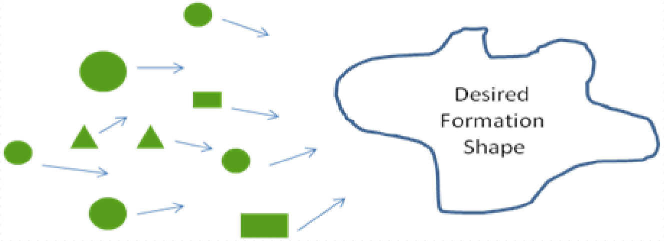
Centralized topologies create single point of failure type systems. We aim to implement a decentralized solution to increase the robustness of the system.





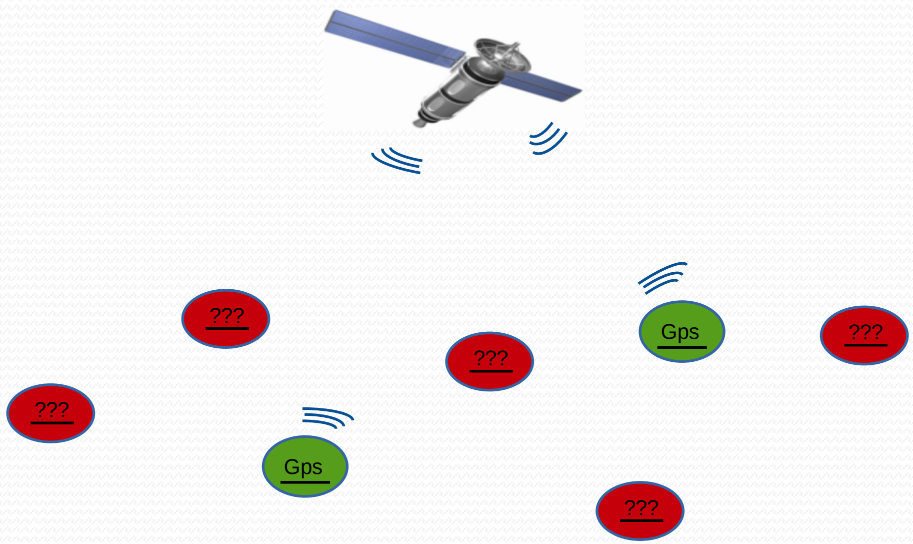
Our aim

•Designing a formation control system with a **decentralized** topology



Motivation - 4

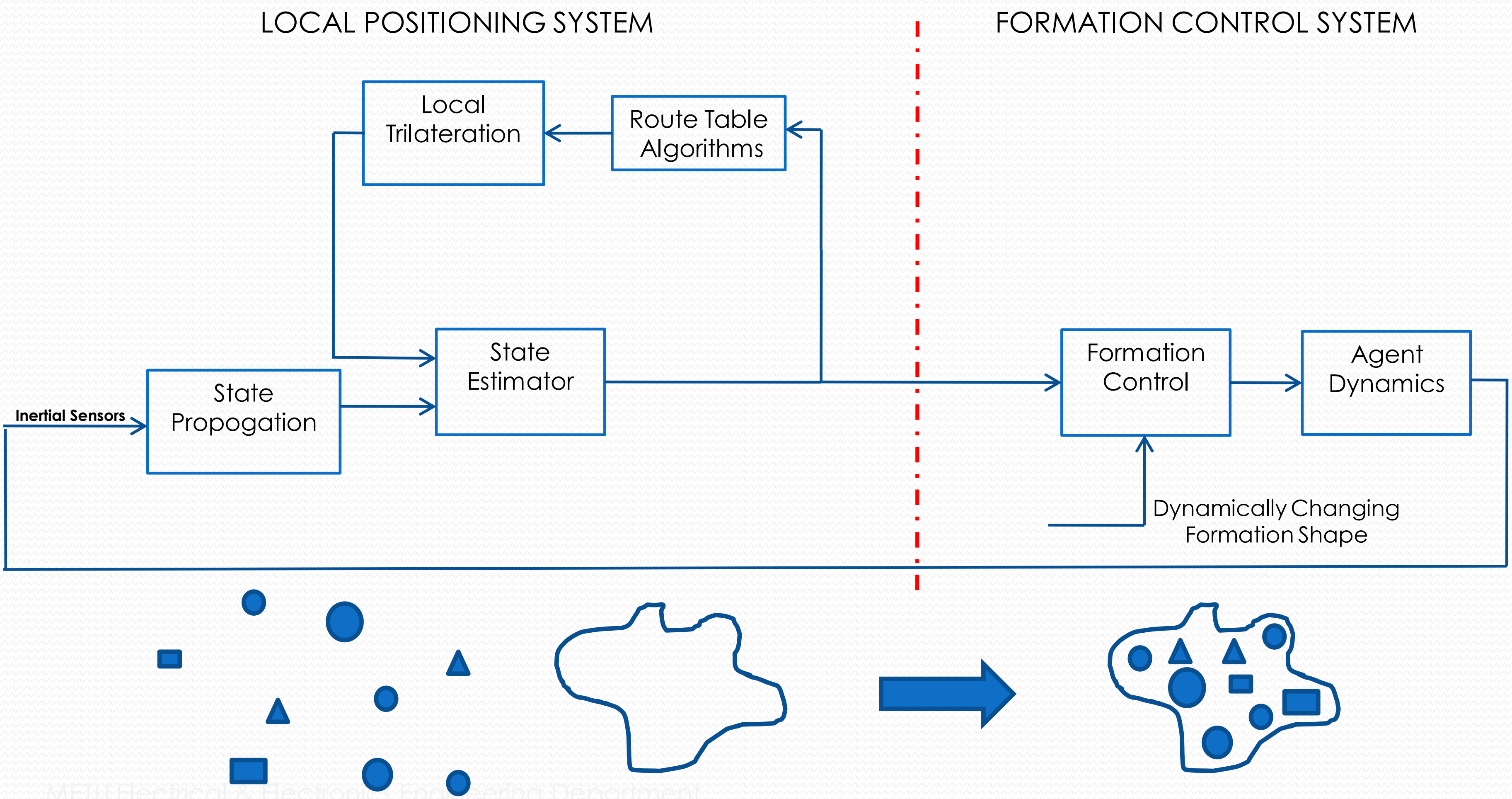
Most of the related works assume that the position data is always available (i.e. can be measured) for each agent in the workspace.



Our aim

- Designing a local positioning system to provide position information to the second type agents with the help of position beacons.

System Overview



METU Electrical & Electronics Engineering Department

Local Positioning System (LPS)

Local positioning system is composed of two main parts.

<u>Local Trilateration</u>

Calculates the positions of the second type agents using position beacons as their direct neighbors.

<u>Route Table Determination</u>

Determines the route tables for agents in the swarm.

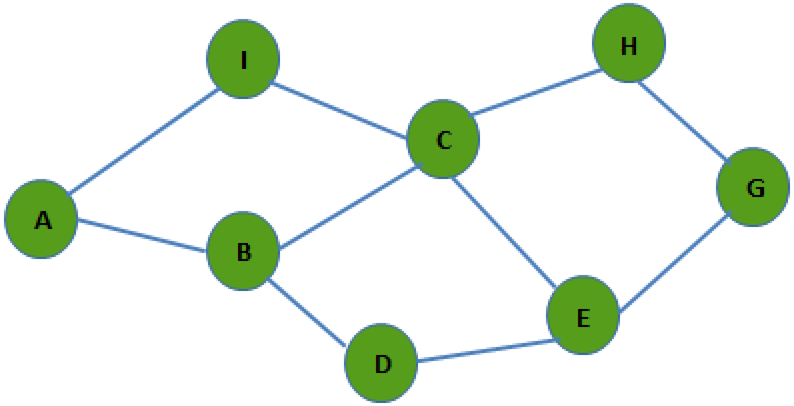
Local Positioning System (LPS)

1)Route Table Determination

- Destination-Sequenced Distance Vector Routing Protocol (DSDV) algorithms are used to create the route tables.

Route table for agent B

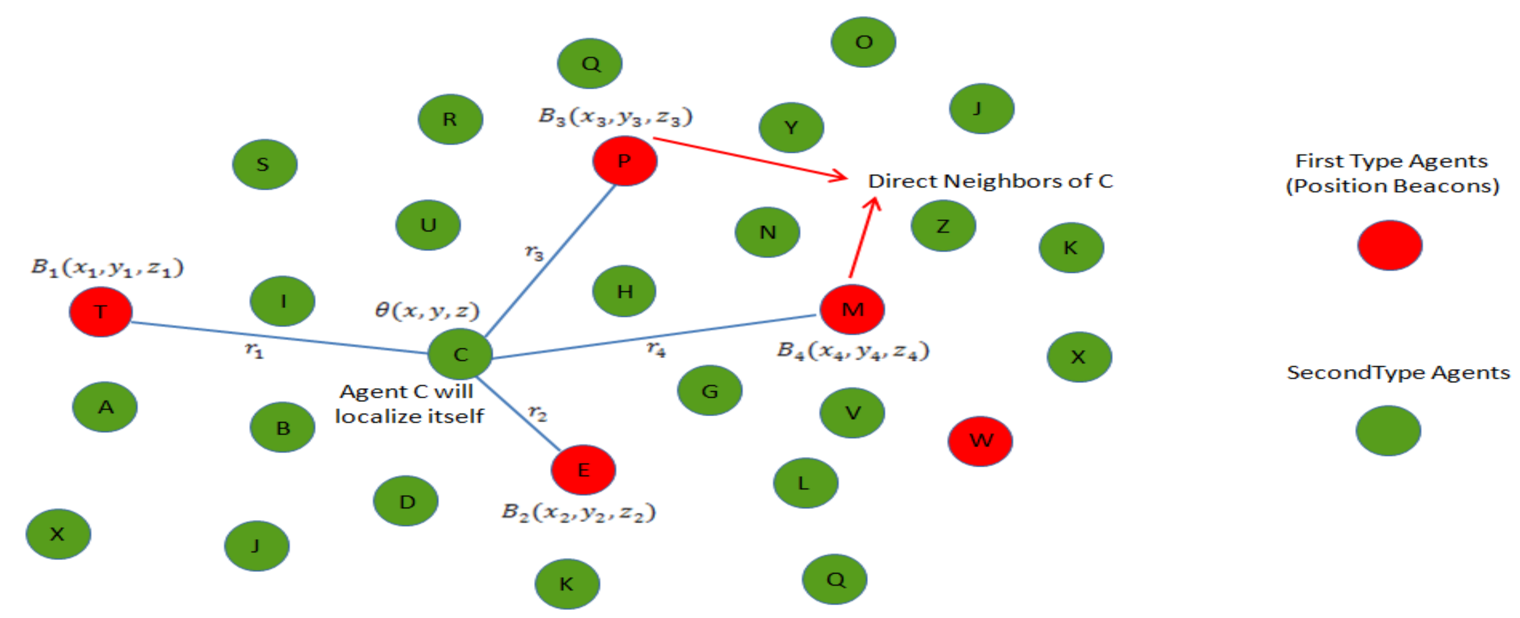
Destination	Next Hop	Cost
A	A	1
I	A	2
C	C	1
H	C	2
G	C	3
E	D	2



Local Positioning System (LPS)

2)Local trilateration

- Calculates the position of an agent with the help of position beacons which are direct neighbors.



Formation Control System

Three different approaches are used to design the formation control system in this thesis work.

Formation Control Strategies

Potential Field Based Approach

1) Artificial Forces Method

- Directly calculates control laws based upon potential fields

Shape Partitioning Based Approaches

2) Bubble Packing Method
3) Randomized Fractals Method

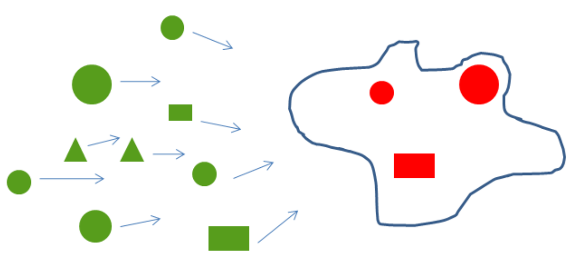
- Partitions the desired formation shape into goal states
- Implements an algorithm to assign agents to goal states

Formation Control System

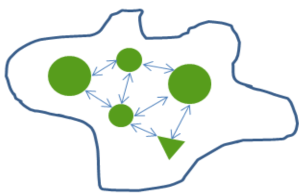
- **Artificial Forces Method**

Directly defines the control law for individuals with different potential field components.

Attractive Forces

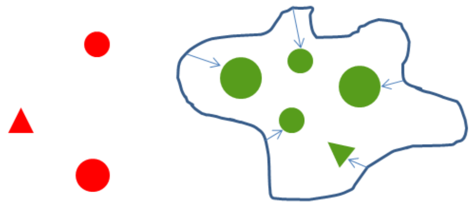


Intermember Forces

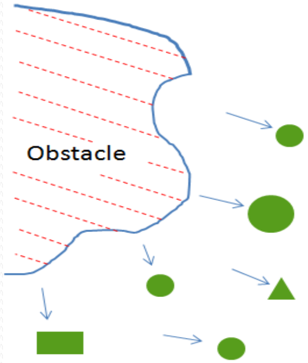


$$u_i = u_{att\_i} + u_{rep\_i} + u_{obs\_i} + u_{int\_i}$$

Repulsive Forces



Obstacle Forces

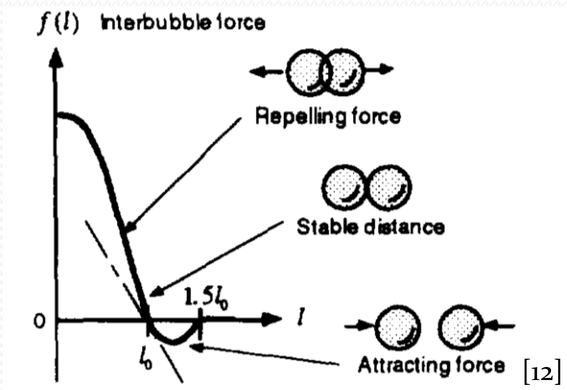


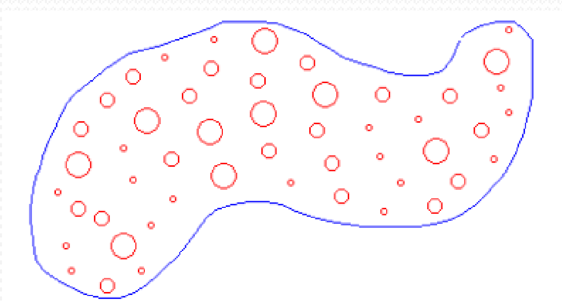
Formation Control System

- **Shape Partitioning Based Approaches – Partitioning Process**

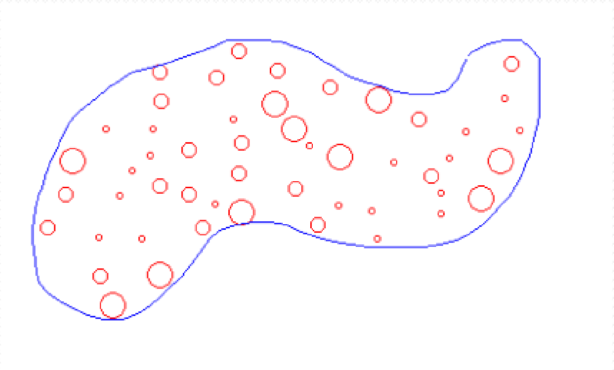
These two methods partition the desired formation shape into goal states with different approaches.

❖ Bubble Packing





❖ Randomized Factals

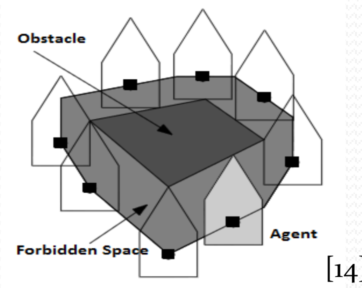


Formation Control System

- **Shape Partitioning Based Approaches – Assignment Process**

The procedure of the assignment of the agents to the goal states are identical.

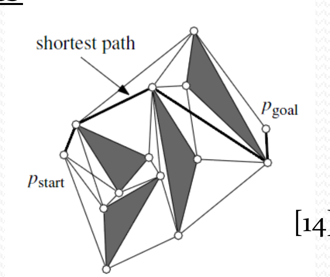
1)Calculation of Free Configuration Space



[14]

Forbidden Space

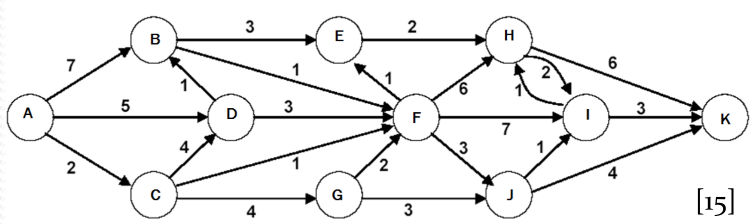
2)Visibility Graphs



[14]

Visibility Graph

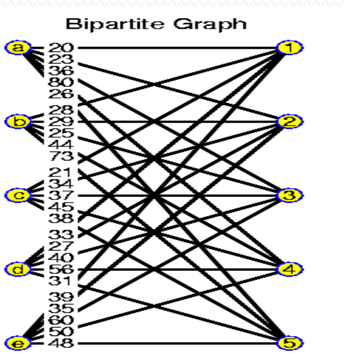
3)Dijkstra's Algorithm



[15]

Calculation of Minimum Shortest Path From A to K

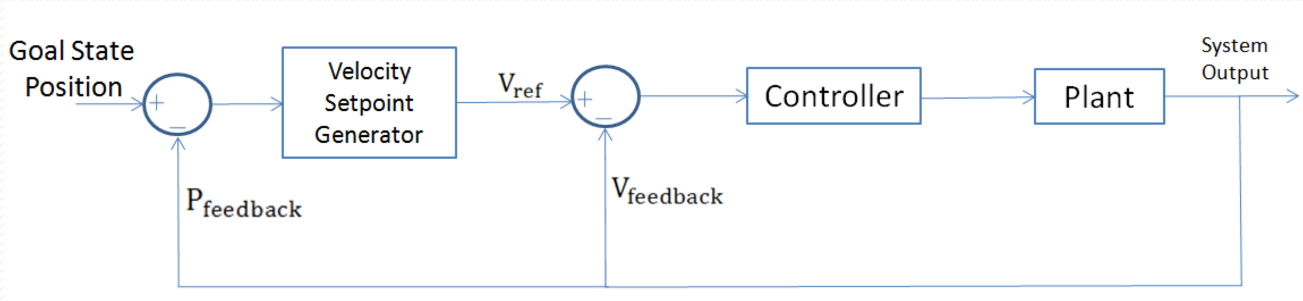
4)Hungarian Algorithm (Munkres Assignment Algorithm)

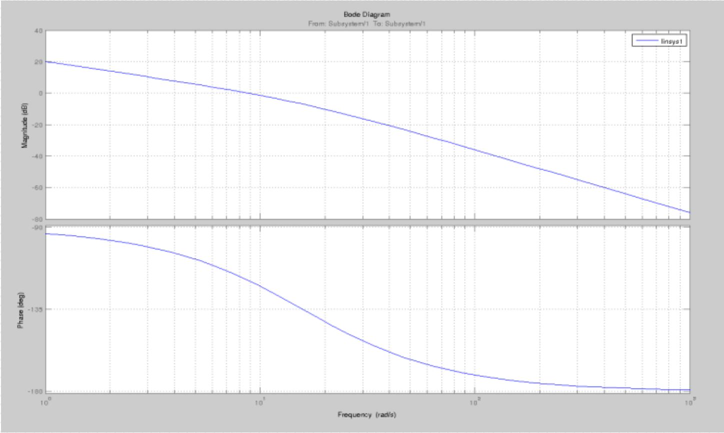


Formation Control System

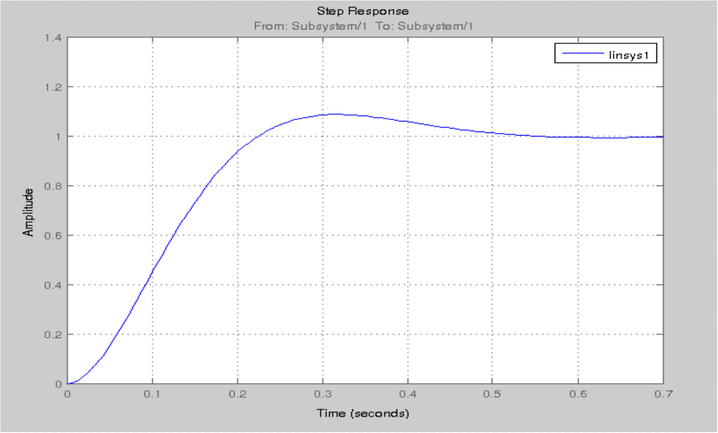
- **Shape Partitioning Based Approaches – Navigation Control**

Navigation to Goal States





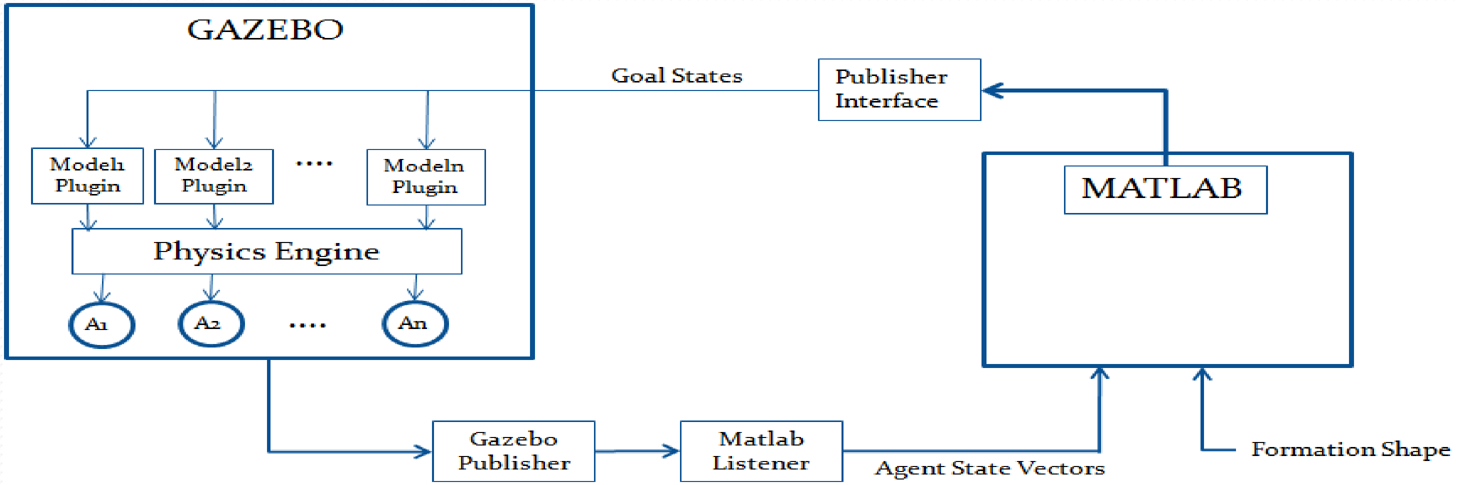
Open loop Bode plots

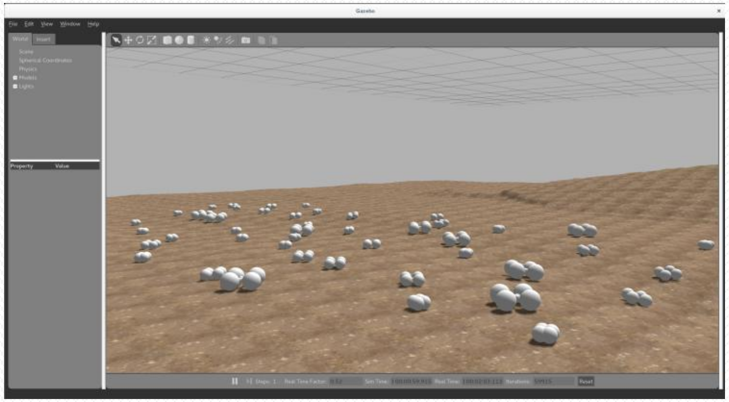


Step response

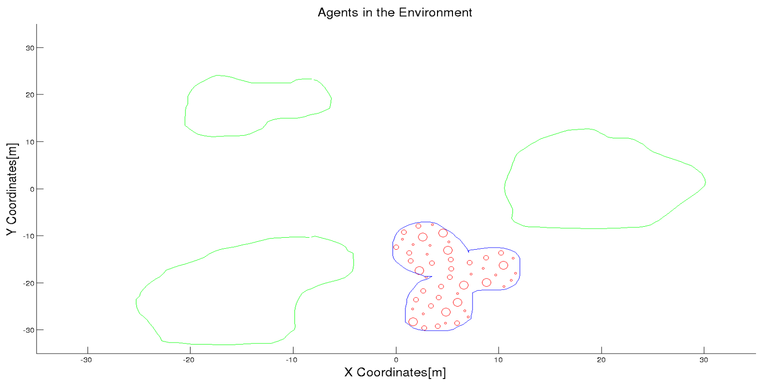
Simulation Results

- Proposed solutions are implemented in a simulation environment.



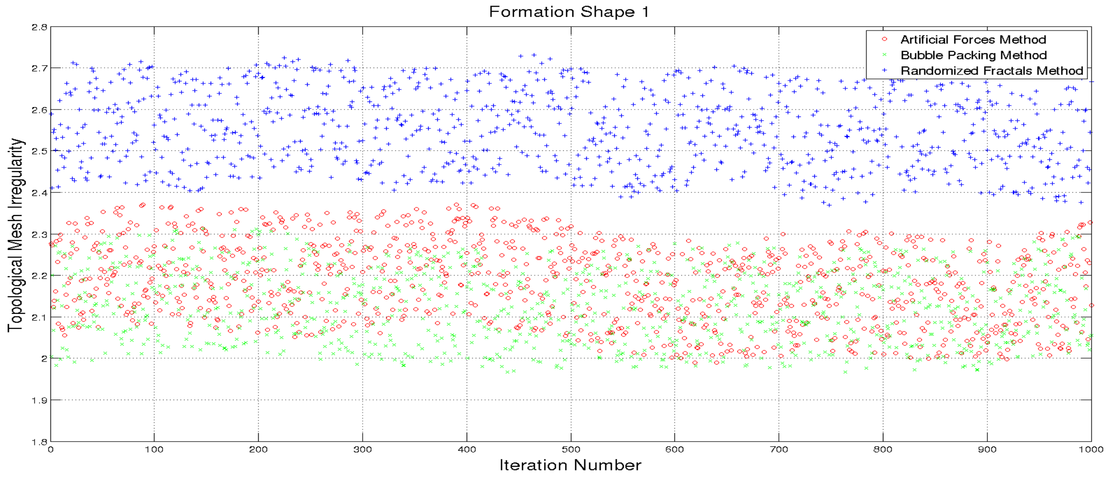


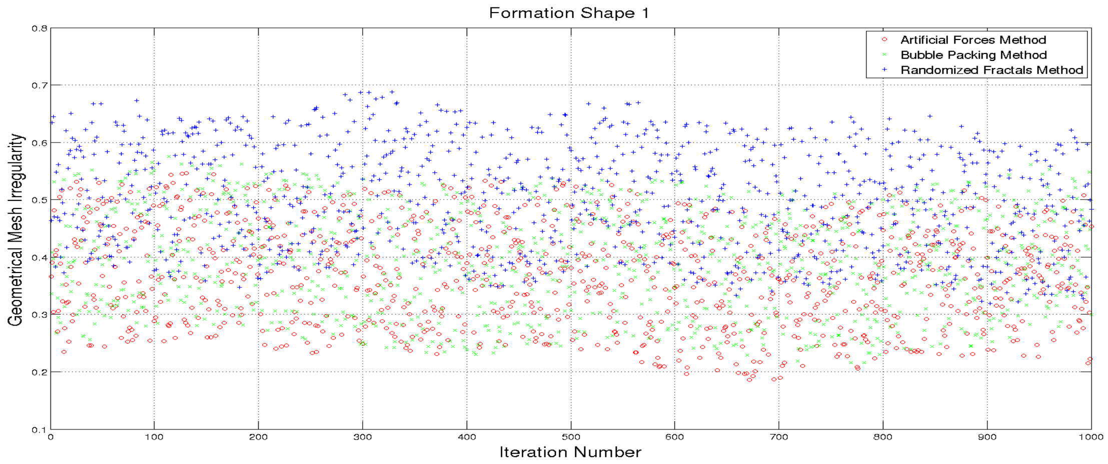
Gazebo Environment



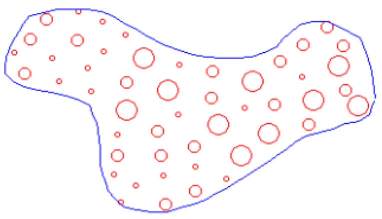
Matlab Environment

Simulation Results – Mesh Quality

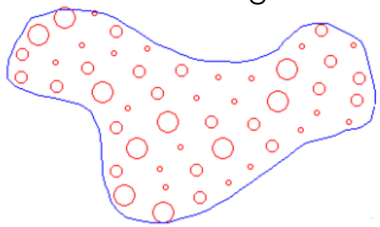




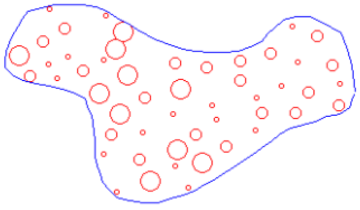
Artificial Forces Method



Bubble Packing Method



Randomized Fractals Method



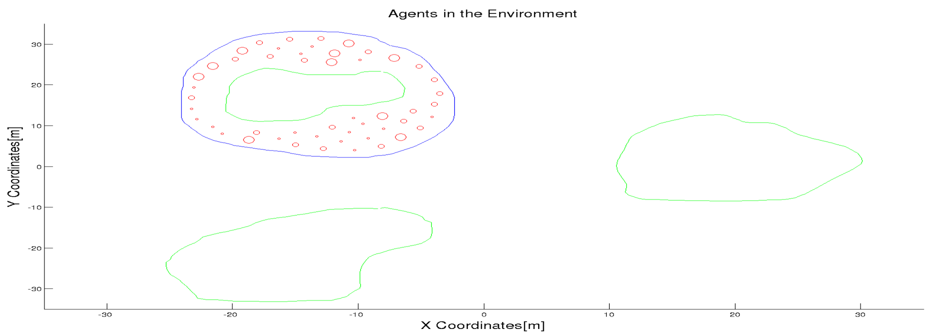
Simulation Results – Comparison of 3 Different Methods

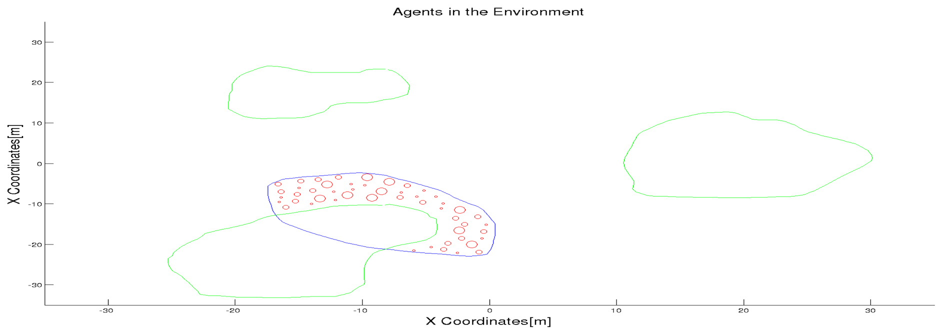
•Comparison of different solution methods are illustrated in Table -1

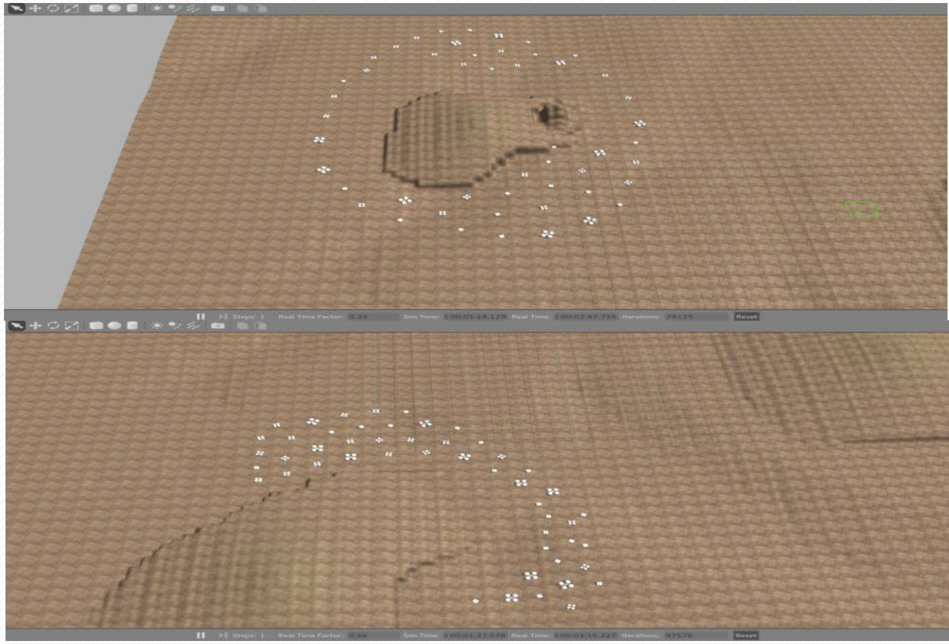
Table -1

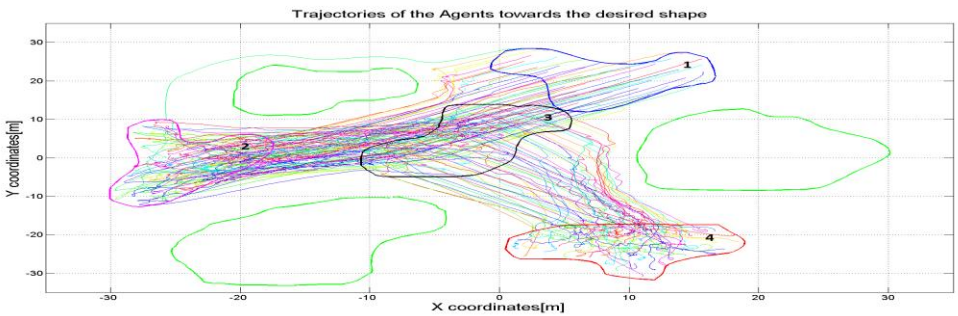
Method/ Metric	Total Displacement	Settling Time	Mesh Quality
Artificial Forces			✓
Bubble Packing	✓	✓	✓
Randomized Fractals	✓	✓	

Simulation Results – Various Formation Shape Trials



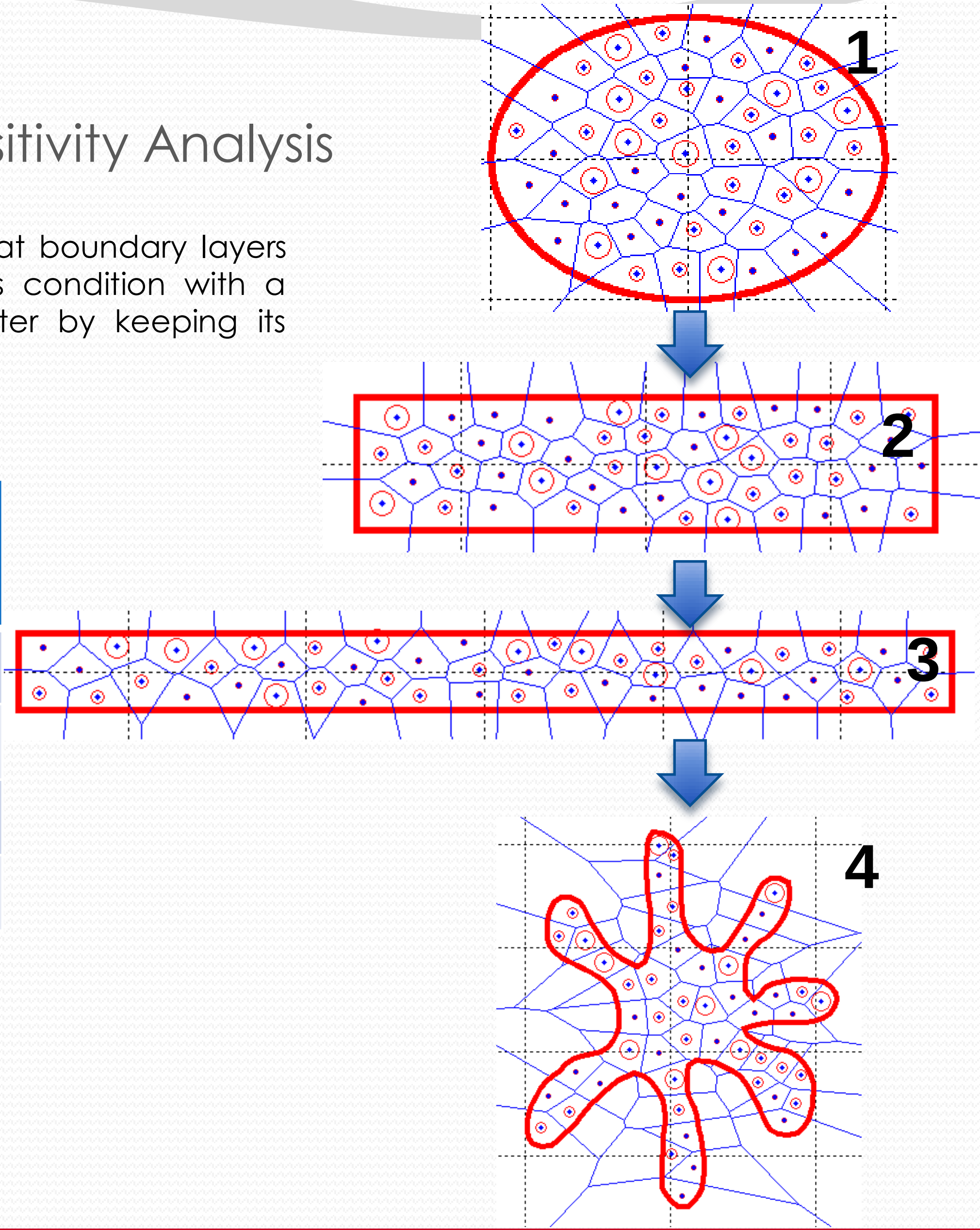






Simulation Results – Sensitivity Analysis

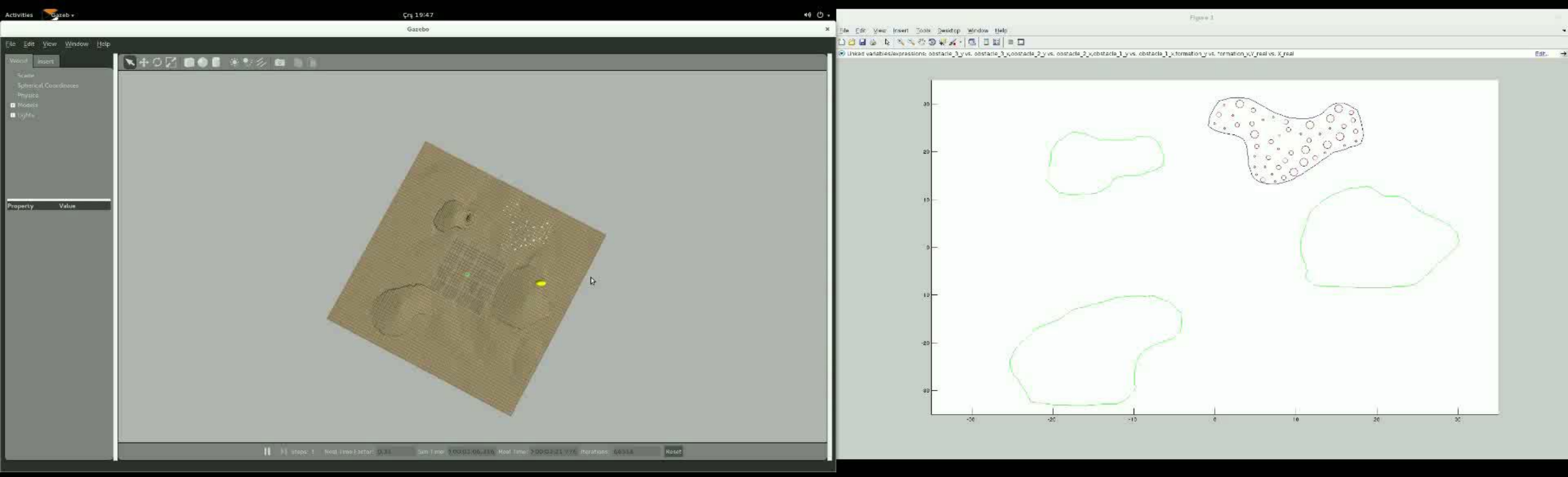
• Mesh irregularities are expected to be increasing at boundary layers due to discontinuties[17]. It is possible to see this condition with a formation shape dynamically changing its perimeter by keeping its coverage area constant.



Shape	Area	Perimeter	Topological Mesh Irregularity
1	314[m^2]	62,8[m]	2,46
2	314[m^2]	82,8[m]	2,96
3	314[m^2]	116,82[m]	3,45
4	314[m^2]	128,36[m]	3,95

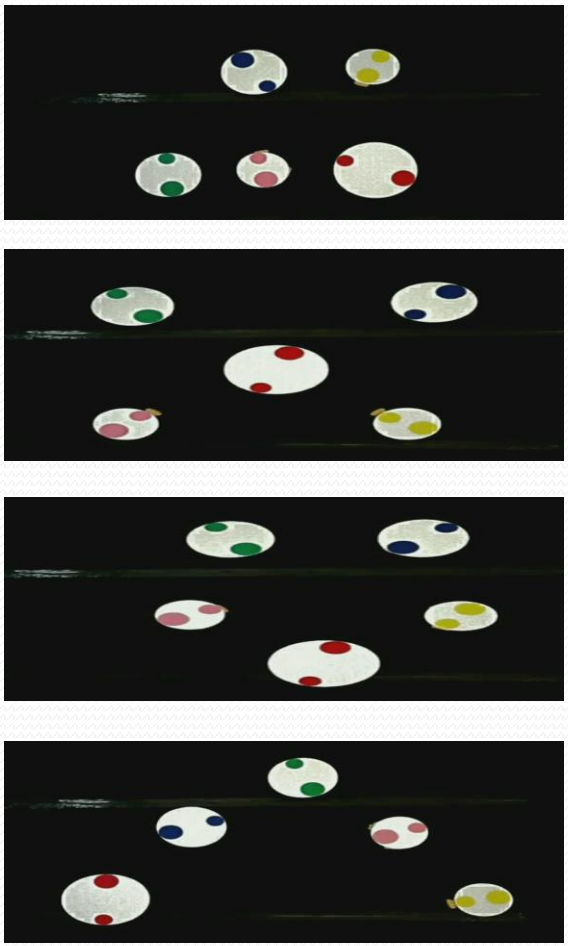
*In 2D, circle has the minimum perimeter to cover a fixed area[18], thus it has the lowest irregularity.

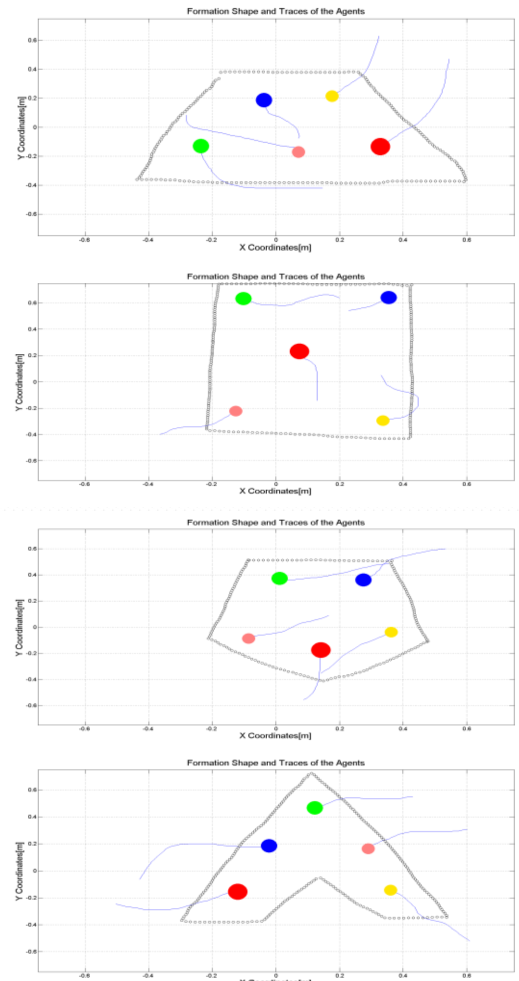
Simulation Results – Dynamical Formation Shapes

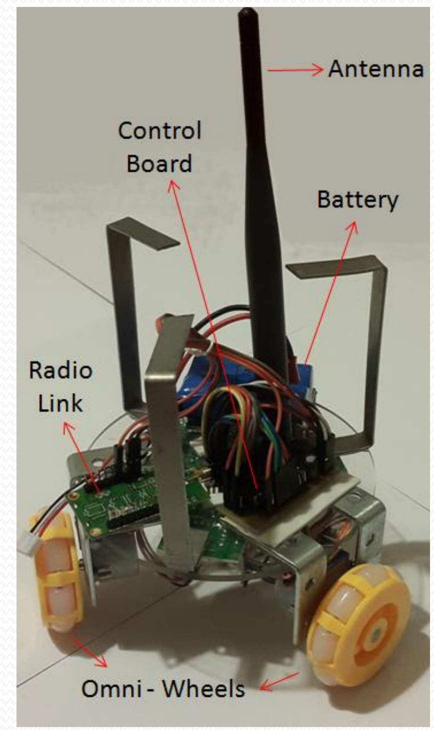


Hardware Implementation Results

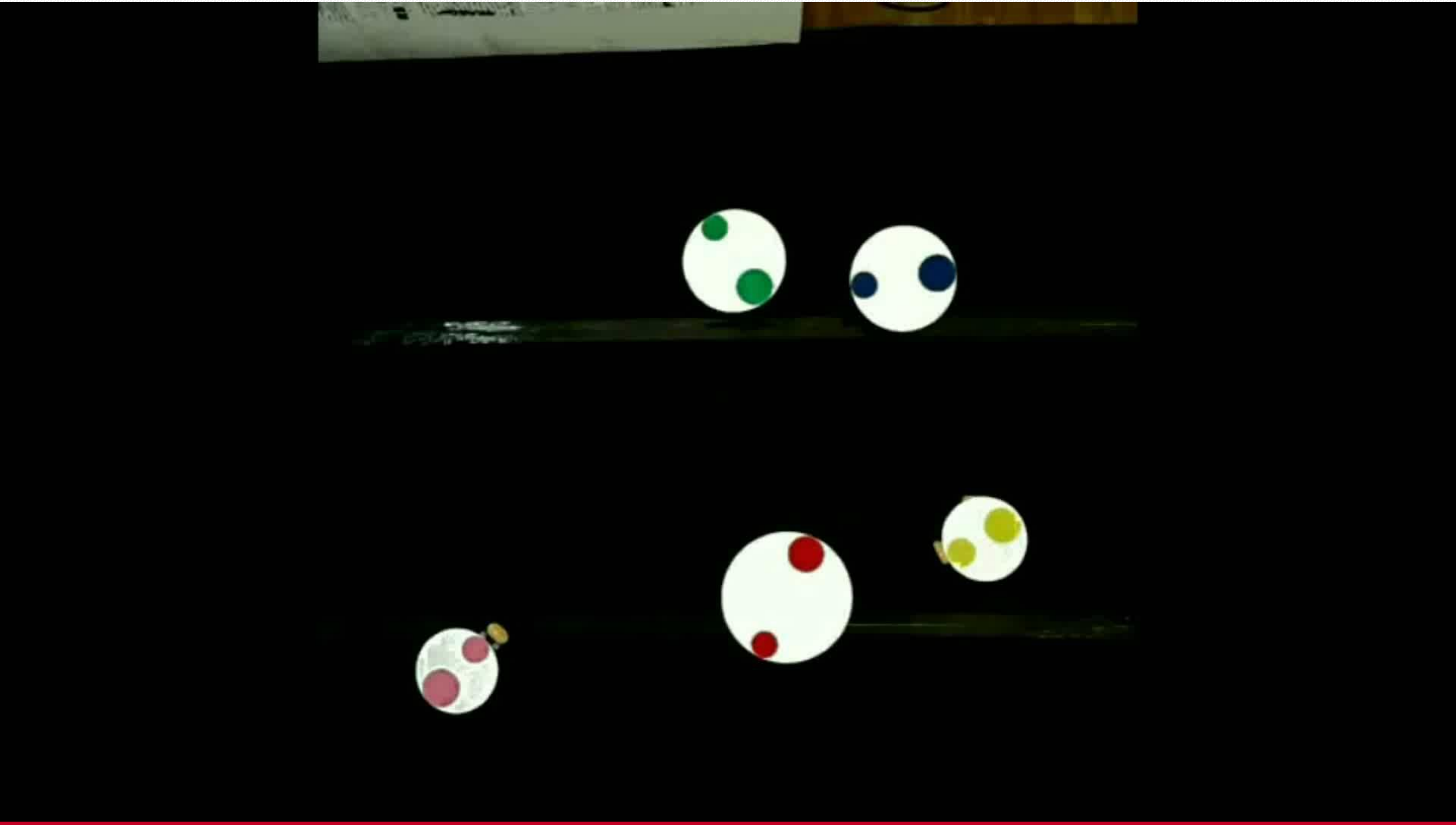
•Hardware applications which implements the methods discussed in this thesis work are also developed







Hardware Implementation Results



Conclusion

•We aim to implement a formation control system with heterogenous agents and complex geometrical shapes which are changing dynamically.

• We have designed a decentralized topology in which each agent contributes on decision process.

•We have implemented a local positioning system to distribute position data to the second type agents.

Future Works

- Hardware implementation will be done with more agents.

- Obstacle avoidance is implemented with potential fields. To avoid unwanted equilibrium states, obstacle avoidance feature will be implemented with a more appropriate way (e.g. Tangent bug algorithm).

- We use heterogenous agents just to cover different formation shapes. In hardware implementation, we will achieve a complex task by operating a special payload with the help of transporter and operator types of agents.

References

- [1] http://www.eecs.harvard.edu/ssr/projects/progSA/kilobot.html
- [2] Martin N, Klupar P, "Techsat 21 And Revolutionizing Space Missions Using Mıcrosatellıtes",
- [3] http://www.swarmanoid.org/swarmanoid_hardware.php.html
- [4] S Kornienki, O. Kornienko, and Levi. P. Minimalistic approach towards communication
and perception in microrobotic swarms. In IEEE International Conference on Intelligent Robots and Systems, 2005.
- [5] Farshad Arvin, John Murray, Licheng Shi, Chun Zhang, and Shigang Yue. Development
of an autonomous micro robot for swarm robotics. In IEEE International Conference on Mechatronics and Automation, 2014.
- [6]Touraj Soleymani, Vito Trianni, Michael Bonani, Francesco Mondada, and Marco Dorigo. Bio-inspired construction with mobile robots and compliant pockets. Robotics and Autonomus Systems, 74:340–350, 2015.
- [7] Roderich Grof, Michael Bonani, Mondada Francesco, and Marco Dorigo. Autonomous
self-assembly in a swarm-bot. 22:1115–1130, 2006.
- [8] S.P. Hou, C.C. Cheah, and J.J.E. Slotine. Dynamic region following formationcontrol for a swarm of robots. In ICRA, 2009.
- [9] Samitha Ekanayake and Pubudu Pathirana. Formations of robotic swarm: An artificial force based approach. International Journal of Advanced Robotic Systems,7:173–190, 2010
- [10] http://electronicdesign.com/systems/advanced-robots-swarm-nyc-s-museum-math
- [11] Aveek Das, Rafael Fierro, Vijay Kumar, James Ostrowski, John Spletzer, and Camilla Taylor. A vision-based formation control framework. IEEE Transactions on Robotics and Automation, 18:813–825, 2002.
- [12] Kenji Shimada and David Gossard. Bubble mesh: Automated triangular meshing of non-manifold geometry by sphere packing. In ACM Symposium on Solid Modeling and Applications, 1995.
- [13]John Shier and Paul Bourke. An algorithm for random fractal filling of space.Computer Graphics Forum, 32:89–97, 2013.
- [14] Mark Berg, Otfried Cheong, Kreveld. Marc, and Marc Overmars. ComputationalGeometry. Springer, 1998.
- [15] https://nevraa.wordpress.com/2012/08/08/dijkstra-algoritmasi-ile-en-kisa-yol-bulma/
- [16] Jop Frederik Sibeyn. Graph algorithms. https://www8.cs.umu.se/ jopsi/dinf504/chap14.shtml, last visited on April 2016.
- [17] Richard, Pletcher and John C. Tannehill, Computational Fluid Mechanics and Heat Transfer, Third Edition
- [18] B.V. Ramana, Higher Engineering Mathematics, The McGraw Hill Companies

Thank you for your attention.
Any Questions?

Formation Control System

- Bubble Packing and Randomized Fractals Methods

Velocity Controller

The dynamical system of agents is augmented with an artificial error state, to design an State feedback with LQR controller;

$$\begin{bmatrix} \dot{v} \\ \dot{e} \end{bmatrix} = \begin{bmatrix} -b/m & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} v \\ e \end{bmatrix} + \begin{bmatrix} 1/m \\ 0 \end{bmatrix} F_{net} \qquad y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} v \\ e \end{bmatrix}$$

Q and R matrices used in solving Riccati equations,

$$Q = \begin{bmatrix} q_1 & 0 \\ 0 & q_2 \end{bmatrix} ; R = \rho r_1 \qquad q_1 = \frac{1}{t_{s_1}(x_{1max})^2} ; q_2 = \frac{1}{t_2(x_{2max})^2} \; and \; r_1 = \frac{1}{(u_{1max})^2}$$

where,

$t_{s_i}: desired\ settling\ time\ for\ x_i$

$\rho: tradeoff\ regulation\ vs\ control\ effort$

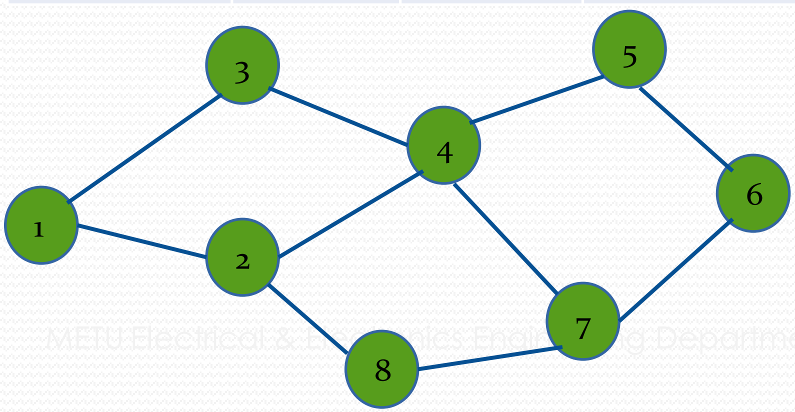
Local Positioning System (LPS)

2)Route Table Determination

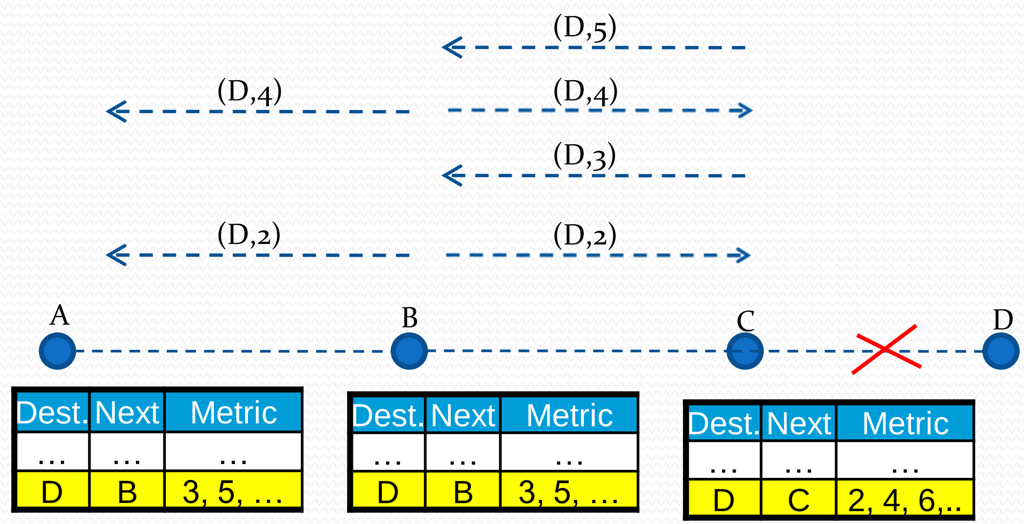
- DSDV is a table driven routing scheme based on Bellman Ford algorithm
- Used to create wireless mesh networks and ad-hoc mobile networks
- Solves routing loop problem in route table algorithms

Route table for agent 2

Destination	Next Hop	Metric	Dest. Seq. No
1	1	1	123
3	3	2	516
4	4	1	212
5	4	2	168
6	8	3	372
7	8	2	432



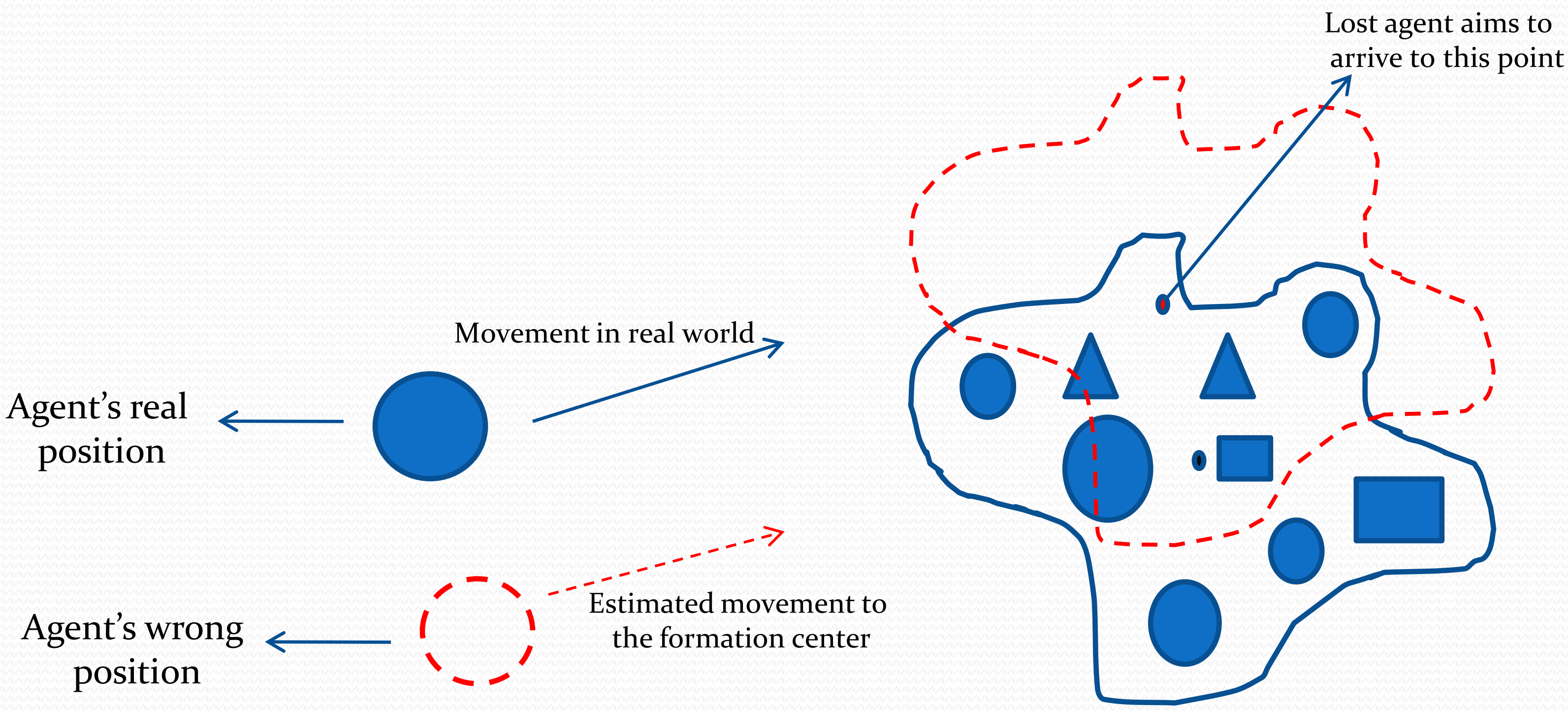
Routing Loop Problem



Local Positioning System (LPS)

1)Local trilateration

Return to Home Mode



Local Positioning System (LPS)

1)Local trilateration

The solution of the position(P(x,y,z)) with the help of positions of neighbors can be reduced to a problem of;

$$\mathrm{A}\vec{\mathrm{x}} = \vec{b}$$

We have an A matrix with a dimension of [n-1] x 2 (where n is the number of neighbors). There are three options for the solution of the problem related with the condition of A matrix,

1) $\hat{x} = A^{-1}.b$, unique solution (if there are 3 neighbors and A is full column rank matrix)
2) $\hat{x} = (A^T A)^{-1} A^T b$, minimum norm solution (if there are more neighbors and A is full column rank matrix
3) Find the minimum error/norm solution with nonlinear least squares method, if rank(A) = 1

Formation Control System

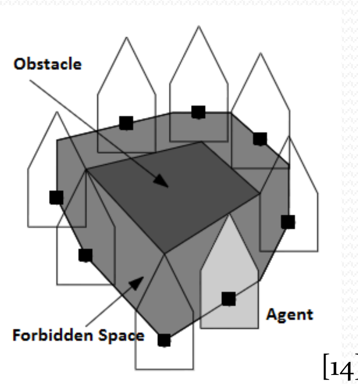
- Bubble Packing and Randomized Fractals Methods

Decision of Goal States

1)Calculation of Free Configuration Space

$$C(R_i) = C_{free}(R_i, S) + C_{forb}(R_i, S)$$

Forbidden Space : $S_1 \oplus S_2 := \{p + q : p \subset S_1, q \subset S_2\}$



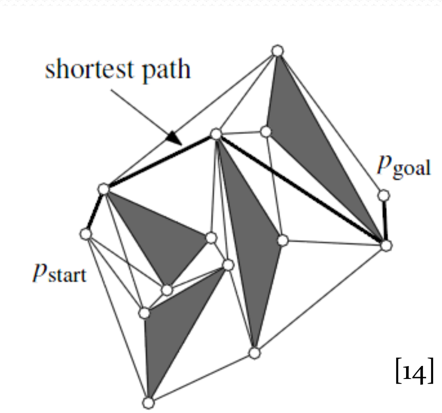
[14]

Forbidden Space

2)Visibility Graphs

The shortest path between a start and goal among a set S of augmented polygonal obstacles consists of arcs of the visibility graph [14]

$$\gamma_{vis}(S^*) \text{ where } S^* := S \cup \{p_{start}, p_{goal}\}$$



[14]

Visibility Graph

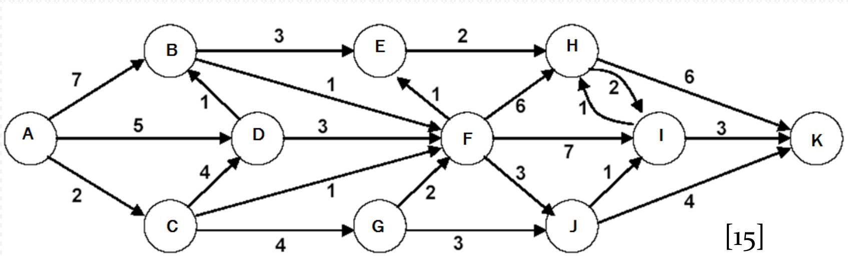
Formation Control System

- Bubble Packing and Randomized Fractals Methods

Decision of Goal States

3)Dijkstra's Algorithm

Dijkstra's algorithm is a tree search algorithm for finding the shortest paths between nodes in a graph

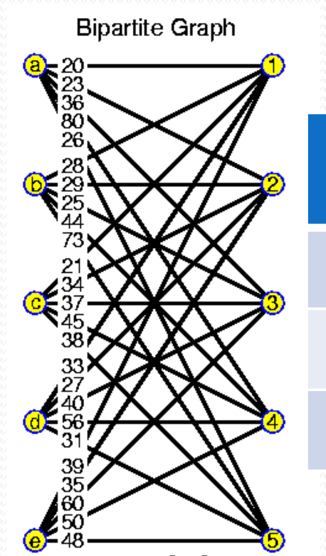


[15]

Calculation of Minimum Shortest Path From A to K

4)Hungarian Algorithm (Munkres Assignment Algorithm)

The shortest path between a start and goal among a set S of augmented polygonal obstacles consists of arcs of the visibility graph



[16]

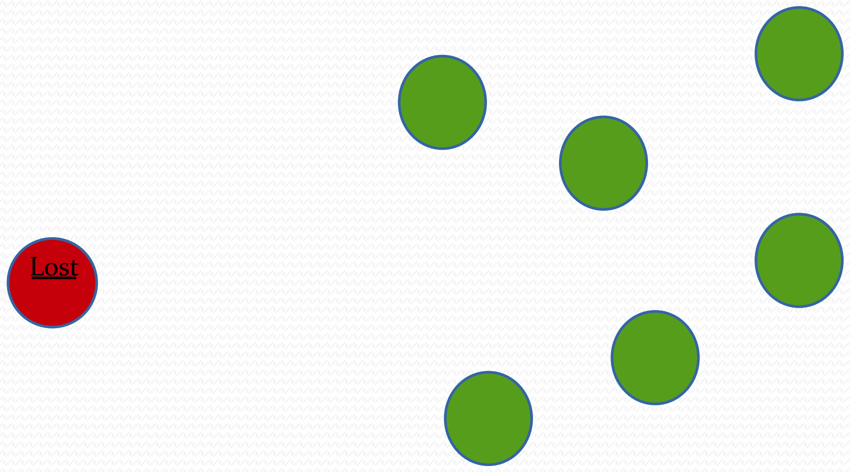
	Clean Bathroom	Sweep Floors	Wash Windows
Jim	\$3	\$2	\$7
Steve	\$2	\$5	\$3
Alan	\$4	\$3	\$2

Local Positioning System (LPS)

2)Local trilateration

Lost agent handling rules;

•An agent is called ‘lost’ when it doesn’t have minimum 3 position beacons as neighbors
•If an agent is lost it cannot enter the localization process, and it enters ‘Lost’ mode in which it is directed to the center of formation shape.



Results

Local Positioning System (LPS)