Hybrid System Modeling for UAV Adversarial Operations

Problem Statement

Large adversarial environment, contains many areas of interest with different number of SAMs.

- Development of team strategies in the presence of team adversarial behavior.
- Dynamic configuration strategy for UAV teams to perform high-level tasks.
  - Design adversarial forces as "Red" and friendly forces as " Blue"
  - Example:
  - High Value Asset Recovery Scenarios

Challenges

What is the most adequate form of organization?

How can the organization adapt to changes in the adversarial behaviour?

Related Work

- A class of hybrid-state continuous-time dynamic systems, Witsenhausen, 1966.
- Controlled vehicle exchange and allocation in dynamic teams, Justin, Girard and De Sousa, 2005
- Task Planning and Execution for UAV Teams. Sousa, Simsek and Varaiya, 2004.
- Efficient Coordination of Multiple-Aircraft Systems, Ribichini, and Frazzoli, 2003

- Unmanned Air Vehicle Adversarial Operations, *accepted for AIAA Guidance, Navigation and Control Conference* ,M. Faied, and A. Girard. 2008.
- Hybrid System Modeling for UAV Adversarial Operations, *submitted in ASME Control Conference* , M. Faied, and A. Girard, 2008.
- Modeling Team Adversarial Action in UAV Operations, *Proceeding of RTO-MP-AVT-146* , A. Girard ,De Sousa, and M. Faied, 2007.

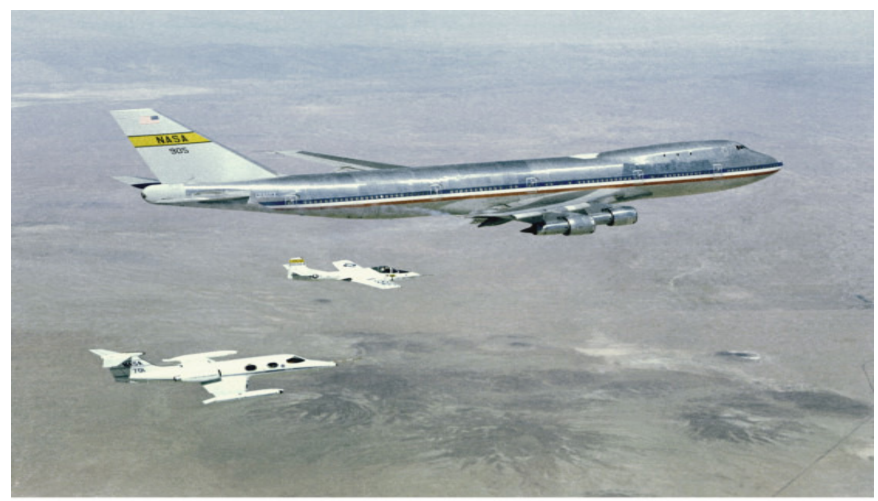
Our Model

- SAMs Configurations
  - With Command Center
  - Without Command Center

- UAVs Configurations
  - One
  - Team

Question

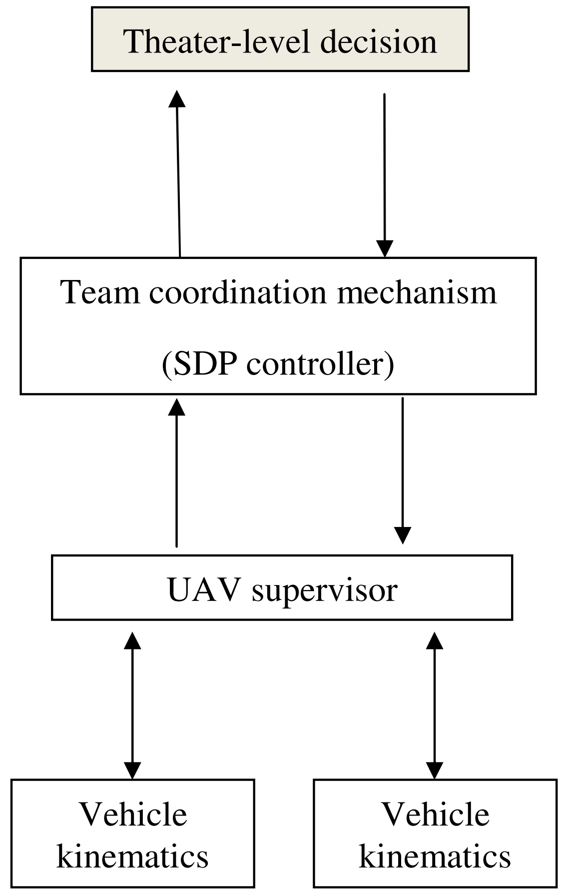
Should we send One UAV or a Team of UAVs to target this area now?



Architecture

Theatre-Level Decision

- Overseeing entity in charge of a geographic region.
- Human operator.
- Allocates region for the UAV teams to survey.
- Makes the decision of how many UAVs will target this area.



Architecture

Team Coordination Mechanism

- State equation:

$$x_{k+1} = x_k - (1 - P_{d)u_k}) * e_k$$

- Control constraints:

$$u_k \in \{0,1\}$$

If $u_k = 0$ UAV isolated.
If $u_k = 1$ UAV integrated.

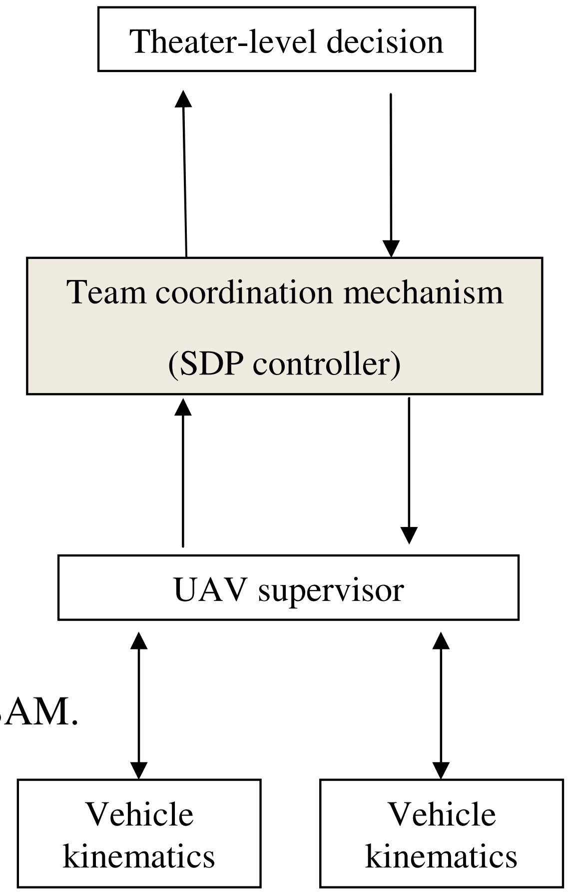
- *Value function at step N:*

$$J_k(x_k) = \max_{u_k=0,1} E\{(1 - P_{d)u_k}) * e_k * (E + J_{k+1}(x_{k+1})) - s_k * P_{d)u_k} * (U + J_{k+1}(x_{k+1}))\}$$

- In our problem, we assume at each of *N* periods two UAVs will attack one SAM.

$$e_k = 1,$$
$$s_k = 2.$$

- Focusing on the relationship between value function and the probability of destruction at step *N*-1 to make the decision (Isolated or Integrated)



Team Coordination Mechanism

- Assume at step N the value function is J_N (it isn't worth it to integrate at step N)

$$\therefore J_N = (1-P_d)*E - 2*P_d*U$$

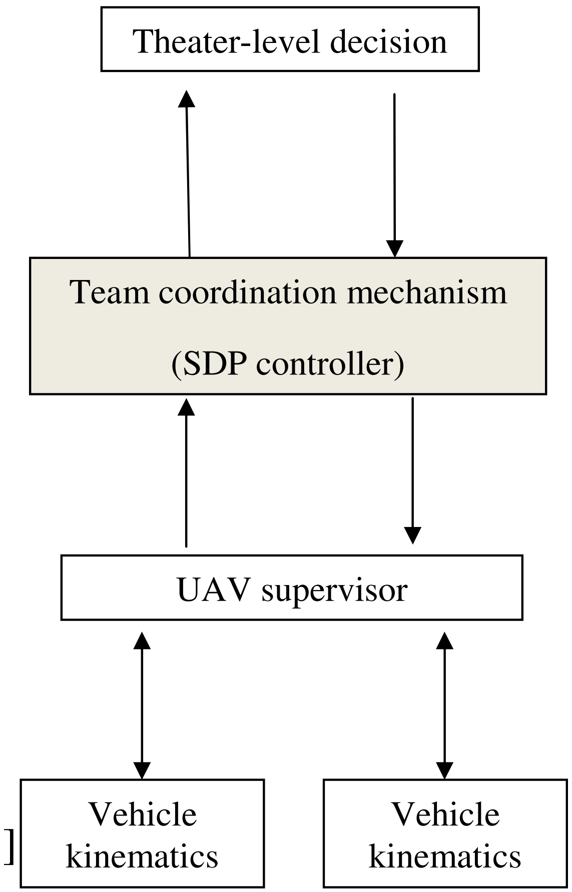
- At step N-1

$$J_{N-1} = \max_{u_k \in U_k} \left\{ \begin{array}{c} [(2-5*P_d+3*P_d^2)*E+(6*P_d^2-4*P_d)*U], \\ [(2-4*k_d*P_d-P_d+3*k_d*P_d^2)*E+(6*k_d*P_d^2-2*k_d*P_d-2*P_d)*U] \end{array} \right\}$$

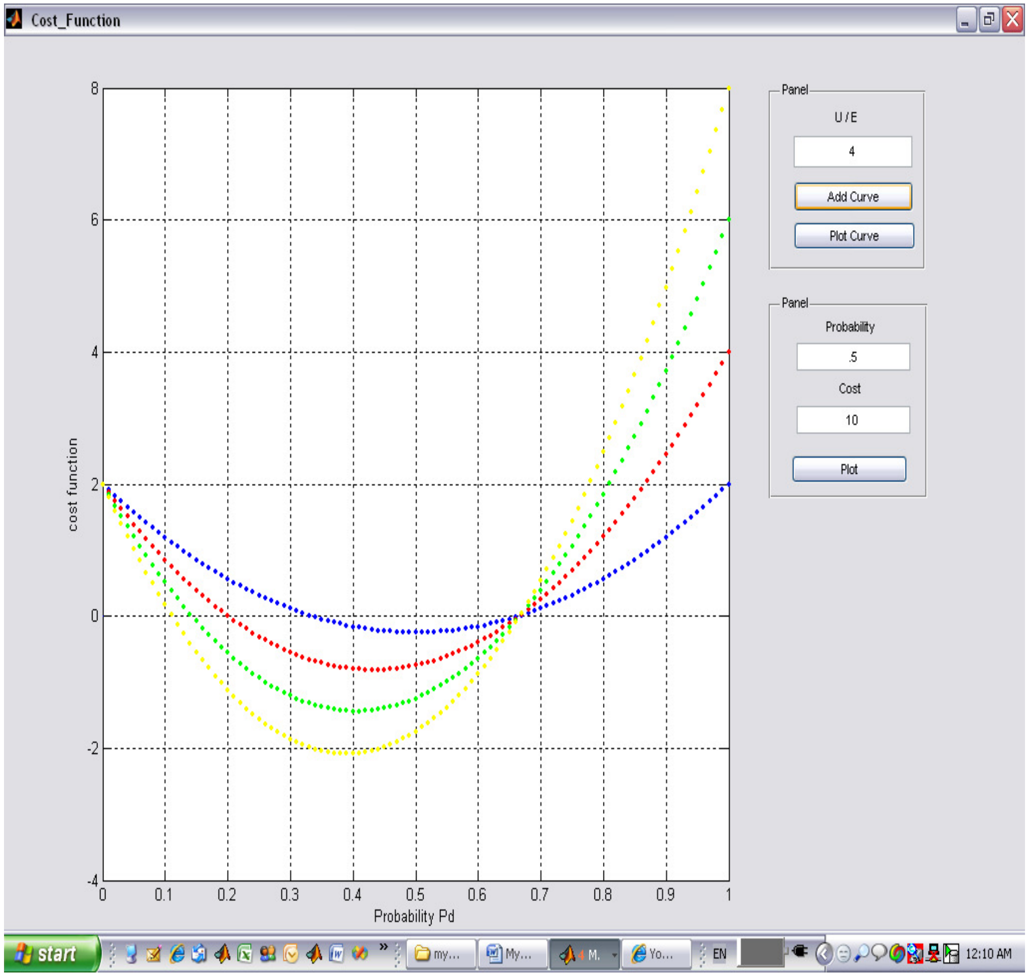
- By equating the "Integrated" value function with "Isolated" value function,

$$J_{N-1} = [(2-5*P_d+3*P_d^2)*E+(6*P_d^2-4*P_d)*U]$$
$$= J_{N-1c} = [(2-4*k_d*P_d-P_d+3*k_d*P_d^2)*E+(6*k_d*P_d^2-2*k_d*P_d-2*P_d)*U]$$

- There is a threshold: before this point "Isolated" always yields the maximum value function and after this point "Integrated" is the maximum value function.



Architecture

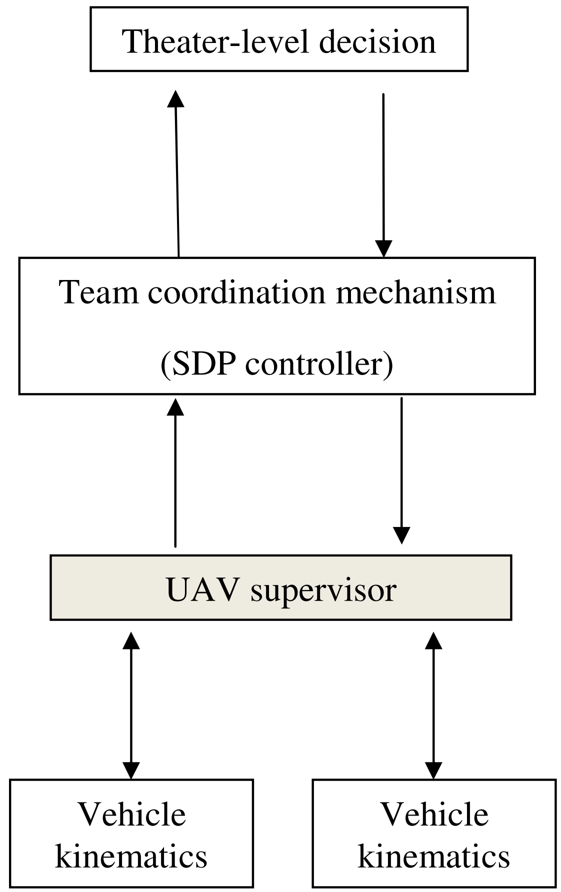


U/E = 1	$Pd_{threshold} = 0.381$
U/E = 2	$Pd_{threshold} = 0.533$
U/E = 10	$Pd_{threshold} = 0.666$

UAV Supervisor

After configuring the team in Team Coordination Layer, this layer is responsible for:

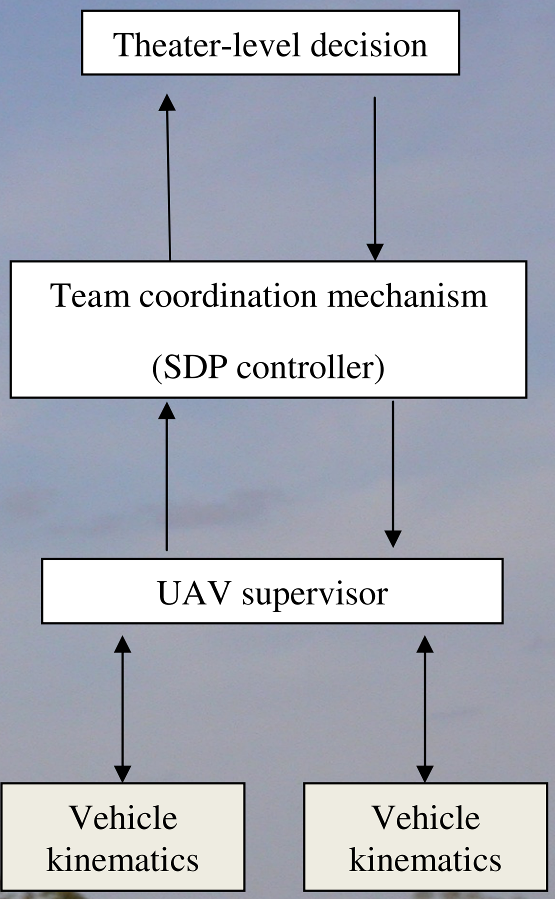
- Path Planning:
  - Min. Risk
  - Path cost
- Object and collision avoidance.



Architecture

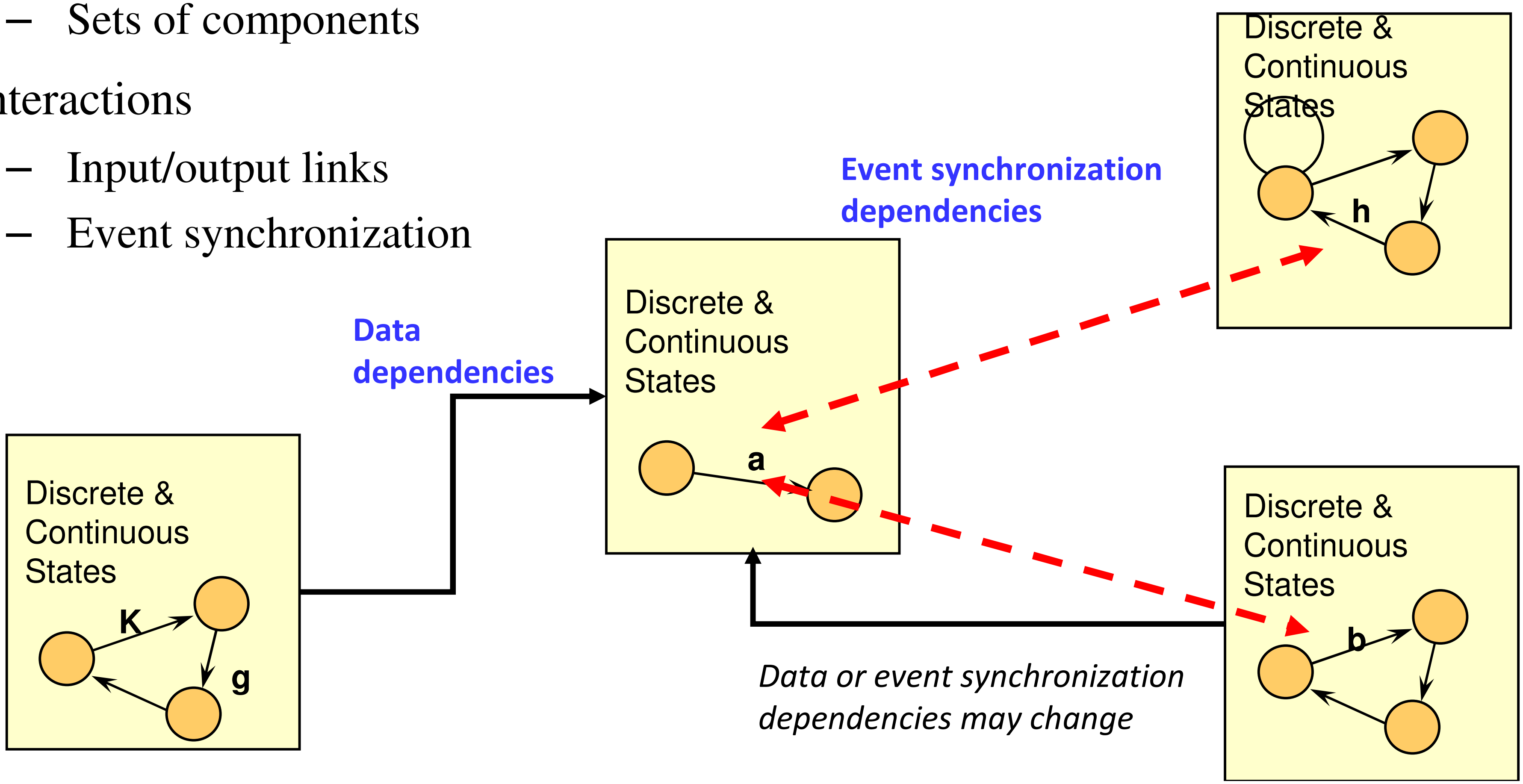
Vehicle Kinematics

- Manhattan grid.
- UAVs will fly at
  - low altitude along streets,
  - constant speed,
  - the cost of 90^o turns is 0 and no 180^o degree turn.



DNHA Framework

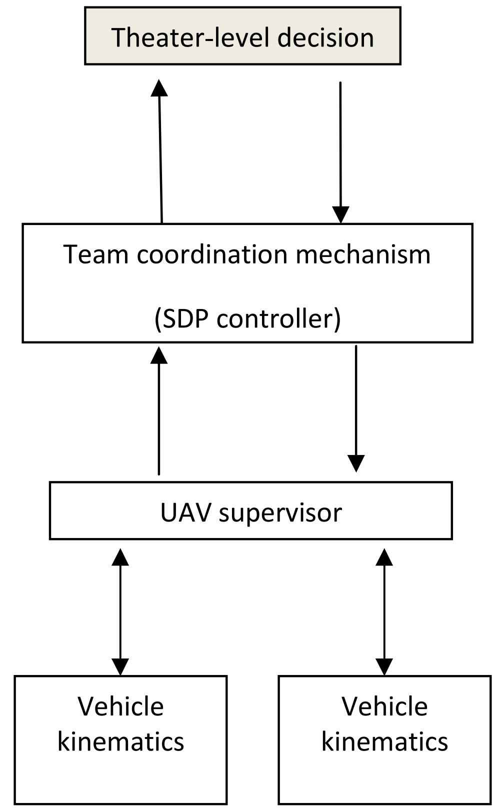
- Entities
  - Components (instances of types)
  - Sets of components
- Interactions
  - Input/output links
  - Event synchronization

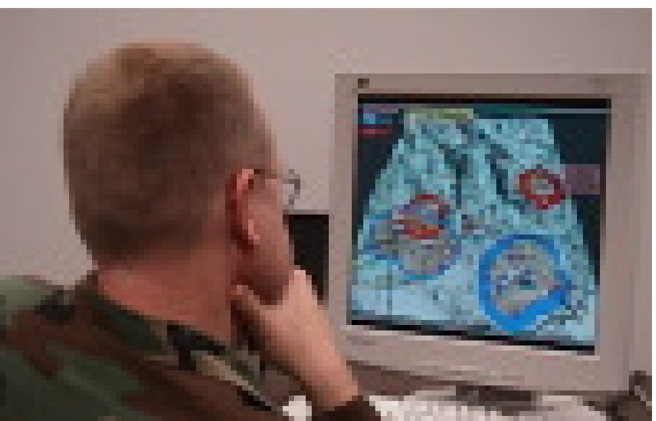


DNHA Framework

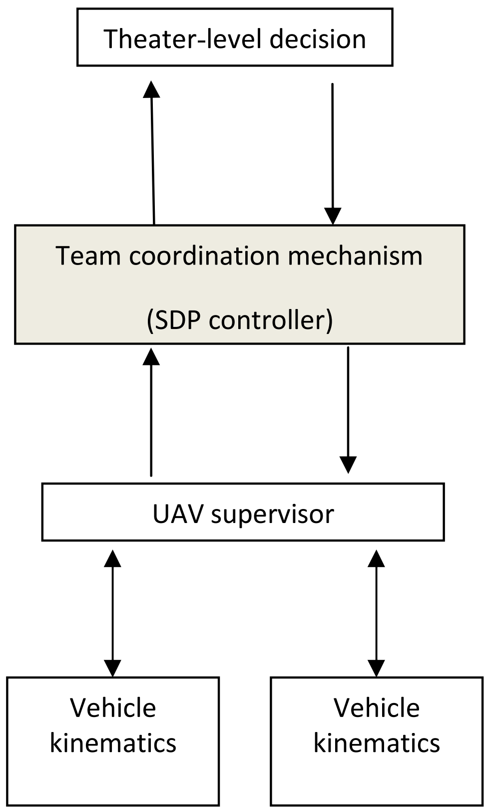
Theater-level decision hybrid automaton

- $T_T = (Q_T, \rightarrow, I_T, O_T, V_T, Init_T)$
- Q_T = {Idle, $Conf_1$, …, $Conf_C$, Error} – ($Conf_1$, …, $Conf_C$. are configurations)
- I_T = {number of SAMs in the target area and their configuration}
- O_T = { number of UAVs in the team}



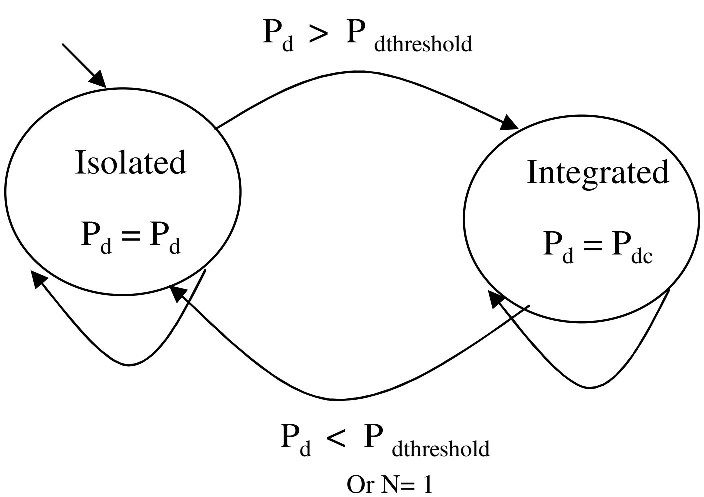


DNHA Framework



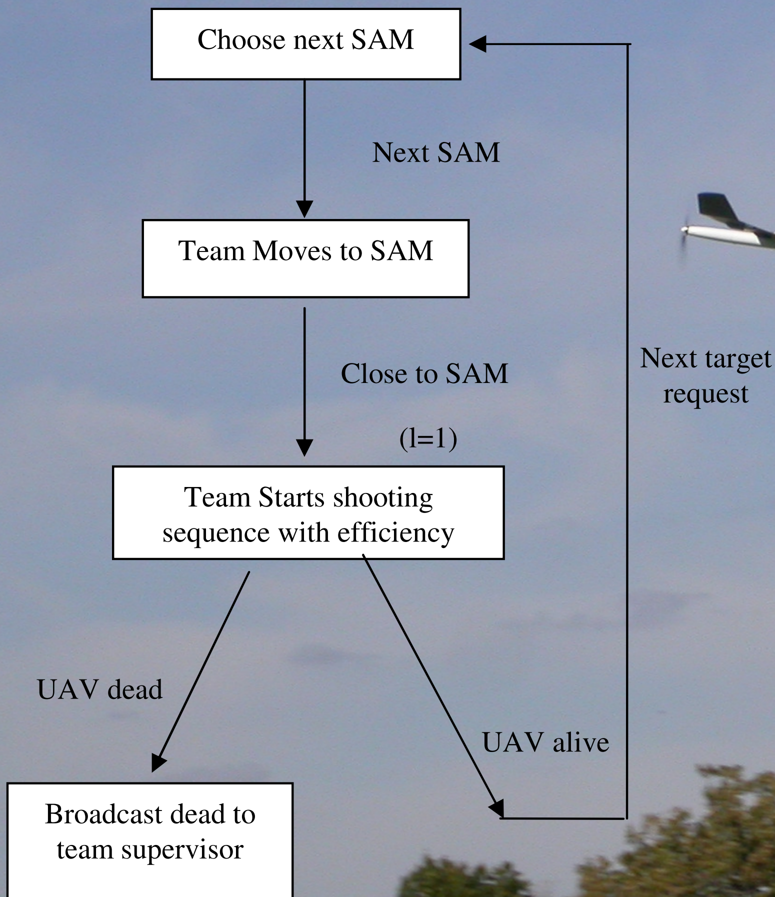
Team Coordination Mechanism HA Representation

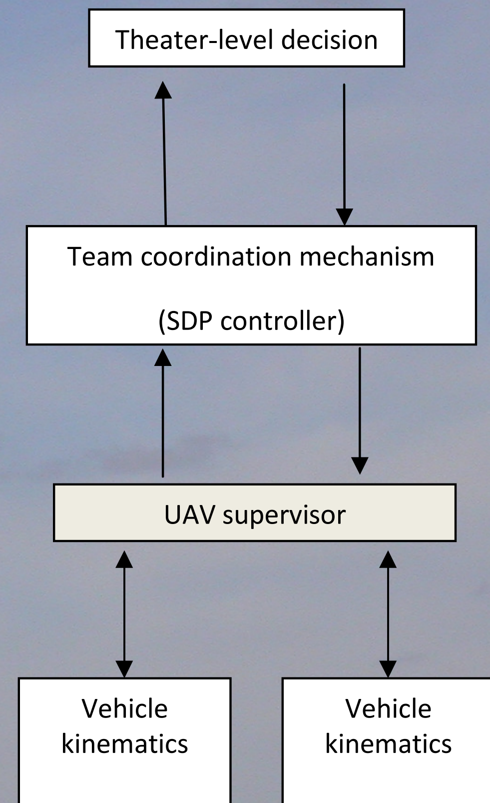
- $T_C = (Q_C, \rightarrow, I_C, O_C, V_C, Init_C)$
- Q_C = {Integrated, Isolated }
- I_C = {number of UAVs in the team, SAMs' configuration and capabilities}
- O_C = {UAVs isolated or integrated}
- $Init_C$ = {Isolated} – the initial state



DNHA Framework

UAV Supervisor HA Representation

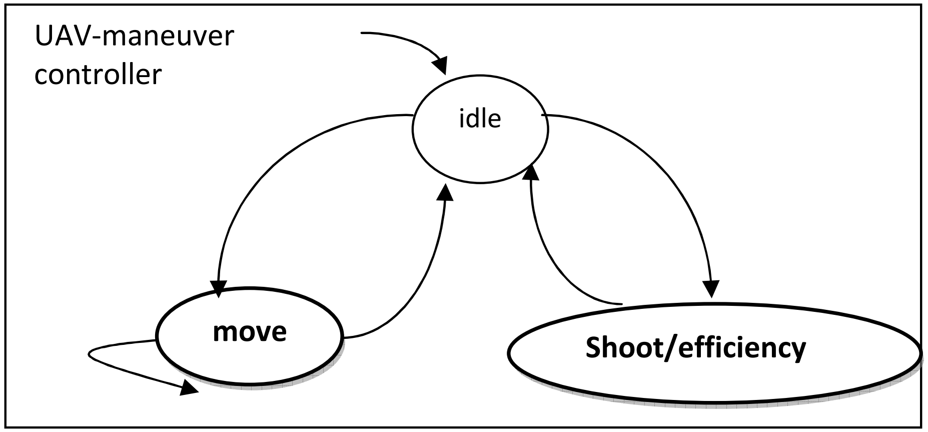




DNHA Framework

UAV Supervisor HA Representation

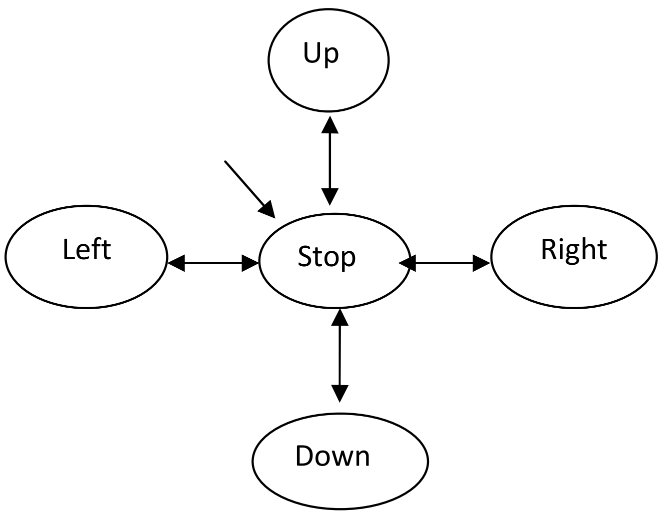
- $T_S = (Q_S, \rightarrow, I_S, O_S, V_S, Init_S)$
- Q_S = {Idle, Move, Shoot}
- I_S = {SAMs locations and configuration}
- O_S = {list-of-messages}– the output events (state messages “go left, go right, go up, go down, live, dead, Tlive, Tdead”) where ‘live’ or ‘dead’ are for UAV status and ‘Tlive’ or ’Tdead’ indicate target SAM status.
- $Init_S$ = {Idle} – the initial state

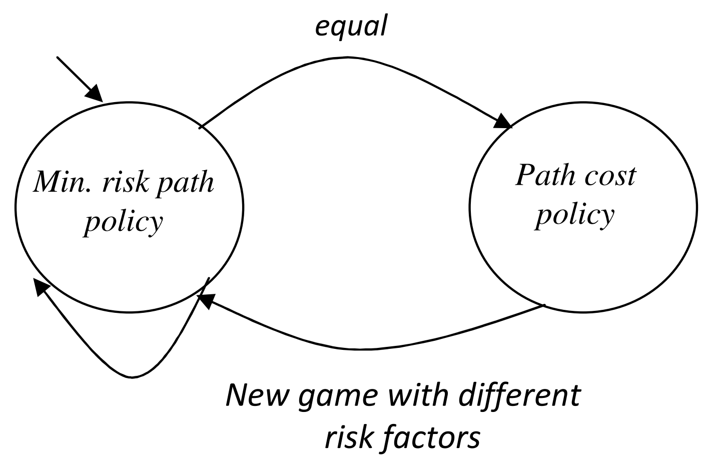


DNHA Framework

UAV Supervisor HA Representation

The "move" sequence can be decomposed hierarchically in two sections: "choose a path policy" and "follow this path".



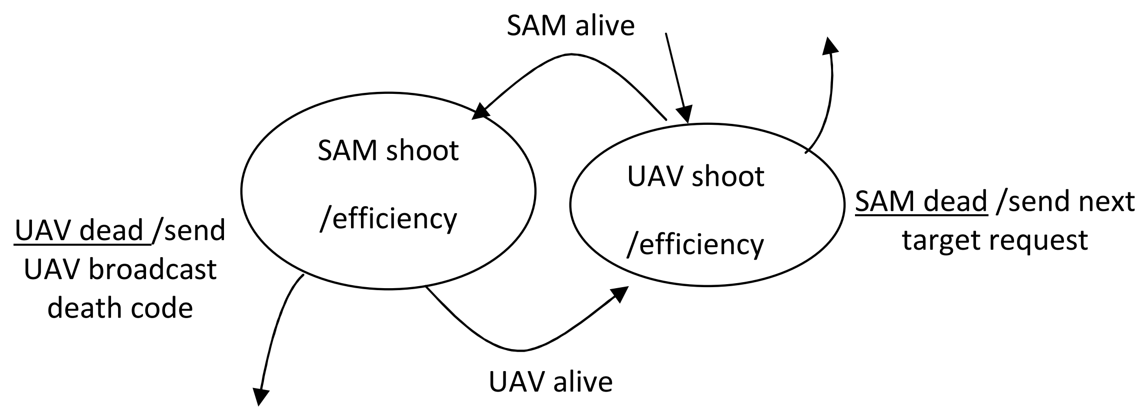


DNHA Framework

UAV Supervisor HA Representation

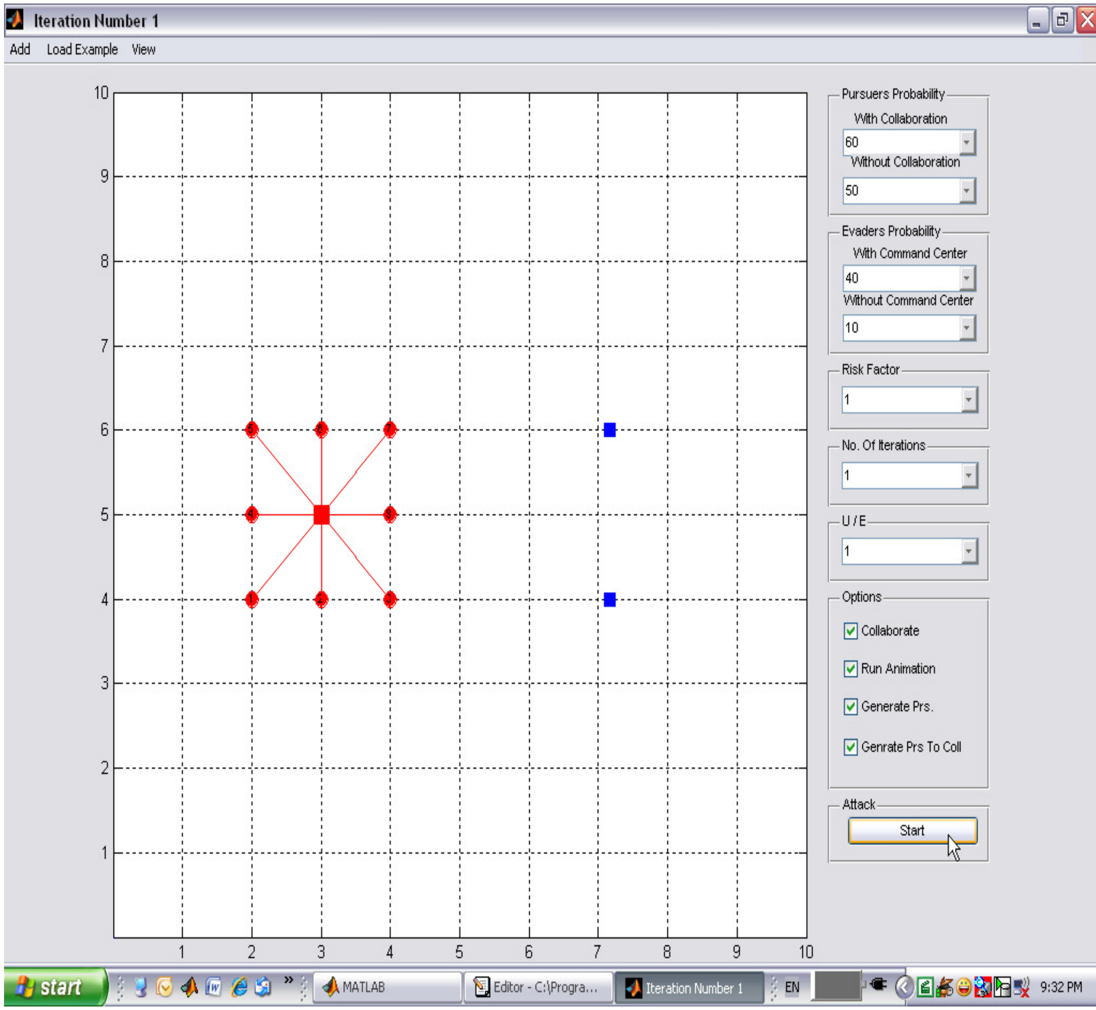
Shoot sequence

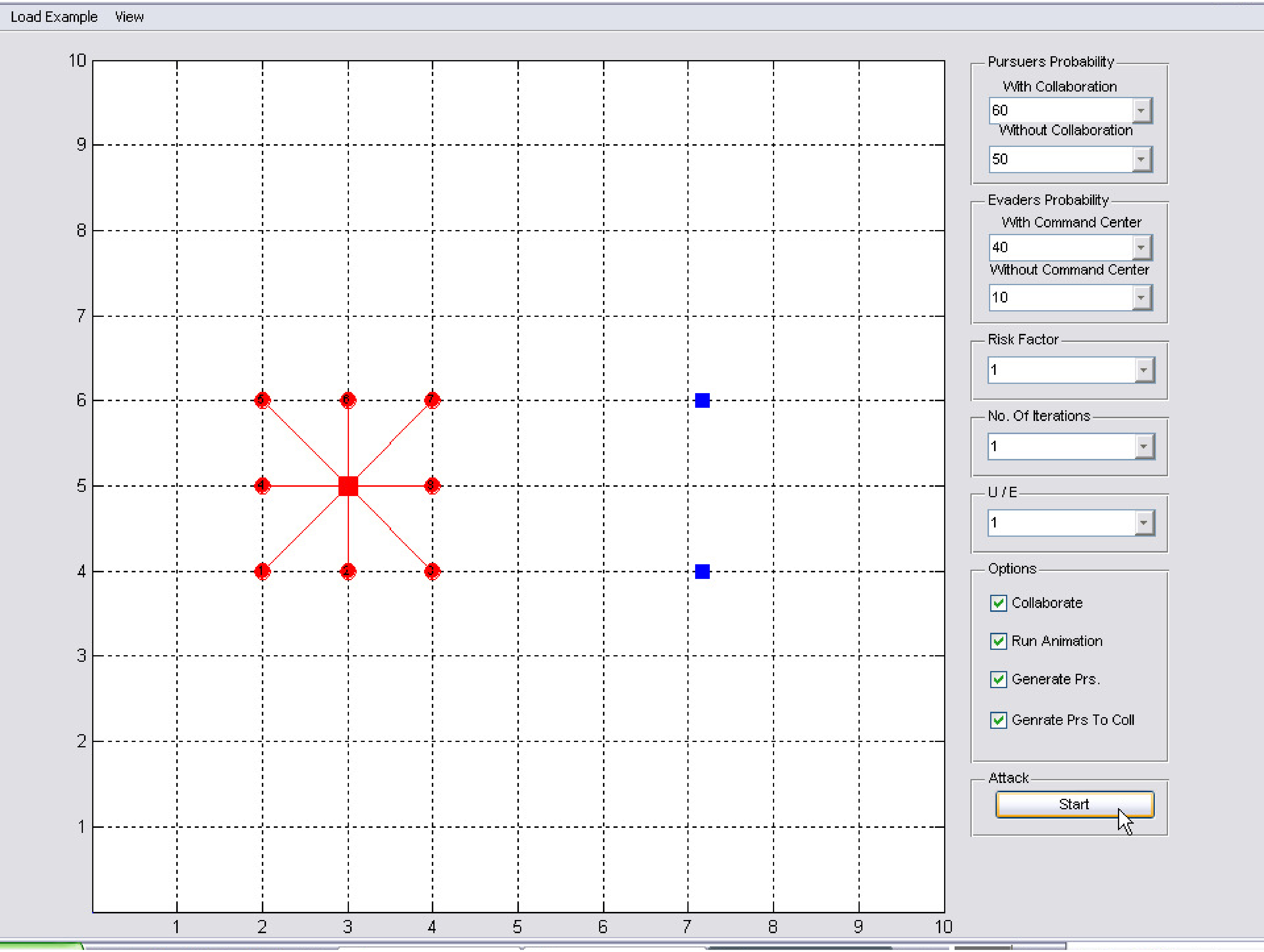
- UAV shoot/efficiency
- SAM shoot/efficiency



Simulation Results

- Evaders
  - ❑ Battery of SAMs + Command Center (CC).
  - ❑ 2 configurations
    - Connected (cc alive).
    - Separated (cc dead).
  - ❑ Probabilities for the SAM to detect/shoot depend on configuration.
- Pursuers
  - ❑ 2 UAVs.
  - ❑ One at a time or work in collaboration.
  - ❑ Lowest risk approach.
  - ❑ When there are several targets it picks the closest one.





Load Example
View
10
9
8
7
6
5
4
3
2
1
1
2
3
4
5
6
7
8
9
10
Pursuers Probability
With Collaboration
60
Without Collaboration
50
Evaders Probability
With Command Center
40
Without Command Center
10
Risk Factor
1
No. Of Iterations
1
U / E
1
Options
Collaborate
Run Animation
Generate Prs.
Genrate Prs To Coll
Attack
Start

Simulation Results

P_d	integrated mode	isolated mode
$P_d = 0.33$	Ave Cost)$_{10}$ = 0.22	Ave Cost)$_{10}$ = 5
	Ave Cost)$_{100}$ = 1.32	Ave Cost)$_{100}$ = 5.5
$P_d = 0.66$	Ave Cost)$_{10}$ = - 1.11	Ave Cost)$_{10}$ = - 2.44
	Ave Cost)$_{100}$ = - 1.39	Ave Cost)$_{100}$ = - 2.59

TABLE 1. SIMULATION RESULT FOR U/E = 2

Note: for U/E = 2, $P_{dthreshold} = 0.5333$

Conclusions

•A new game theoretic formulation for cooperative battle management of teamed UAVs.

• We modeled the scheme in the framework of Dynamic Network of Hybrid Automata to represent the evolving structure of the system.

•A stochastic dynamic programming scheme enables UAVs to achieve autonomous battle management in hostile environments.

• The scheme is an integration of four distinct components

I.Theater-level decision

II.Team coordination mechanism (SDP controller)

III.UAV Supervisor.

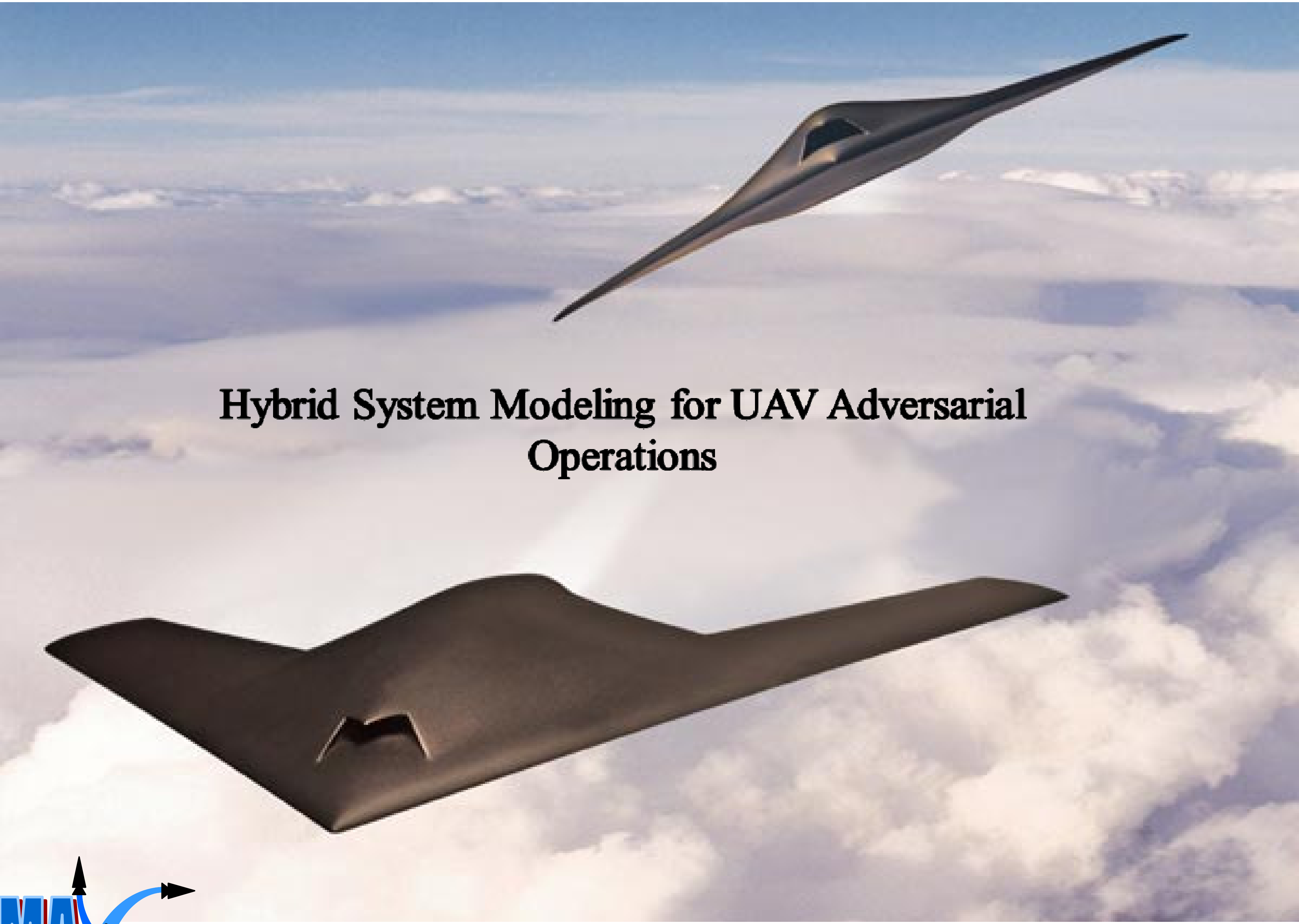
IV.Vehicle kinematics.

• The scheme was implemented in Matlab and demonstrated very effective battle management, path planning and trajectory generation.

SDP methodology is robust enough to incorporate all different variations in hostile environment

Future Work

- Different configurations of enemy SAMs.
- Application to pursuit evasion game.
- Including heterogeneous UAVs



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